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Groundwater vulnerability assessment for nitrate pollution in the Salinas Valley using a modified DRASTIC model

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This Master's Project

Groundwater vulnerability assessment for nitrate pollution in the Salinas Valley using a modified DRASTIC model

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Abstract

Groundwater is an integral piece of California's groundwater resources. One of the most common contaminants present in groundwater is nitrate. Nitrate contamination is often a result of agricultural land use activities on the ground surface. The study area for this analysis is the Salinas Valley Groundwater Basin, an agriculturally dominated basin in coastal California. The Salinas Valley Basin is both one of the most agriculturally productive areas of the state, as well as one of the most nitrate-contaminated basins in the state. The purpose of this research was to develop a groundwater vulnerability map for nitrate pollution in the Salinas Valley. A groundwater vulnerability assessment was carried out using a modified DRASTIC model. DRASTIC is a U.S. EPA rank-sum model for assessing groundwater vulnerability that incorporates depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity. In order to modify the DRASTIC model to assess nitrate contamination specifically, a land use parameter was incorporated into the model. The results of this assessment found 2.9% of the Basin has very low vulnerability, 50.6% has low vulnerability, 42.9% has moderate vulnerability, and 3.6% has high vulnerability. The results of the groundwater vulnerability assessment could not be validated using measured nitrate concentrations in the Basin. Four possible reasons for the poor fit of this assessment have been identified: (1) the temporal variability of select DRASTIC parameters, (2) the inability of the land use parameter to accurately represent nitrate vulnerability, (3) the high spatial variable of nitrate contamination in the Basin, and (4) the static weights assigned to parameters by the DRASTIC model.

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List of Abbreviations

bgs	Below ground surface
CA	California
CASGEM	California Statewide Groundwater Elevation Monitoring
DEM	Digital elevation model
DO	Dissolved oxygen
DVI	DRASTIC Vulnerability Index
DWR	Department of Water Resources
EPA	Environmental Protection Agency
GAMA	Groundwater Ambient Monitoring and Assessment Program
Ksat	Hydraulic Conductivity
MCL	Maximum Contaminant Level
mg/L	Milligrams per liter
NED	National Elevation Dataset
NO_3	Nitrate
NRCS	Natural Resources Conservation Service
NWIS	National Water Information System
SSURGO	Soil Survey Geographic Database
SWRCB	State Water Resources Control Board
U.S.	United States
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

1. INTRODUCTION

Groundwater is a vital source of freshwater worldwide. In the United States, nearly 50% of the population relies on groundwater, while in rural areas this figure may be closer to 90% (Power & Scheppers, 1989; Nolan et al., 2002). Groundwater is used for municipal and domestic drinking supply, as well as for industrial and agricultural purposes. In California, groundwater accounts for 39.6% of freshwater resources in the state (NGWA, 2016). As shown in **Figure 1-1**, irrigation is the primary use of groundwater in California, accounting for 70.7% of groundwater use, while the next largest use, public supply, accounts for 23% of total use (NGWA, 2016).

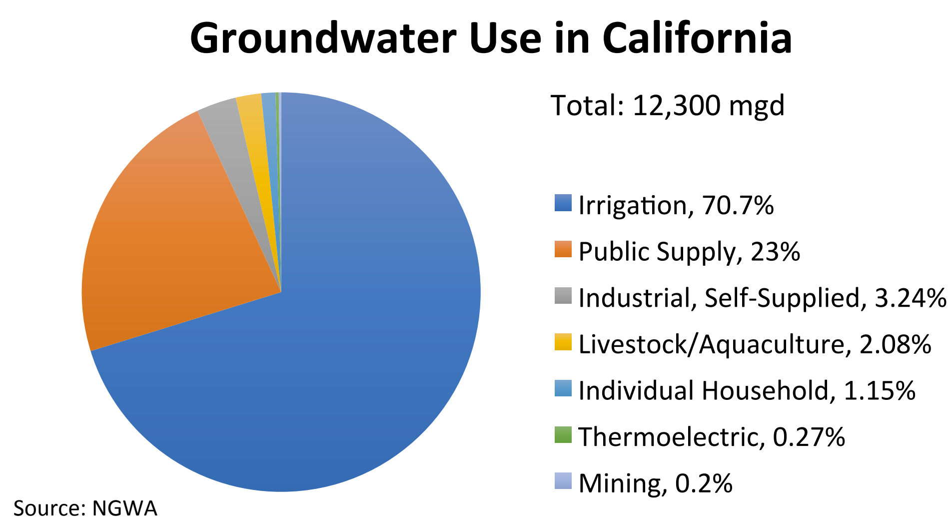

Figure 1-1. Breakdown of groundwater use in California by type, adapted from NGWA, 2016.

One of the most common contaminants present in groundwater is nitrate. Nitrate is a common form of nitrogen, the most abundant gas in Earth's atmosphere. Because many organisms cannot utilize pure nitrogen gas, it is converted by bacteria into other forms, such as nitrate, to be more readily used by organisms (Weiner, 2013). As a result, nitrate is abundant in the environment and present naturally at low levels in groundwater. However, when nitrate concentrations begin to exceed 13 milligrams per liter (mg/L as Nitrate), it is often a sign of nitrate contamination related to anthropogenic activity (Almasri & Kaluarachchi, 2004).

The U.S. Environmental Protection Agency (EPA) has established a maximum contaminant level (MCL) of 45 mg/L for Nitrate (as Nitrate) (U.S. EPA, 2016). Above this level, nitrate is harmful to human health and can cause methemoglobinemia, also known as "blue baby" syndrome, in infants preventing the release of oxygen to tissues, and stomach cancer in adults (Almasri & Kaluarachchi, 2004). Additionally, it has been linked to cases of Non-Hodgkin's Lymphoma (Gardner & Vogel, 2005).

Potential sources of nitrate contamination to groundwater include both point and non-point sources. In agricultural settings, point sources include dairy lagoons and septic tanks, while non-point sources include fertilizers, manure, and leguminous crops (Almasri & Kaluarachchi, 2004). In urban settings, leaking sewers, irrigated areas, contaminated lands, and landfills can act as non-point sources (Lerner & Harris, 2009). Additionally, natural sources can contribute significant amounts of nitrate to groundwater. Leaching from geologic sources, precipitation, and mineralization of organic nitrogen in soils can all contribute to nitrate concentrations in groundwater (Power & Scheppers, 1989).

The most prevalent source of nitrate to groundwater is agricultural land use activity. Many studies have observed a significant correlation between land use activities on the surface and nitrate concentrations in groundwater (McLay et al., 2001; Böhlke, 2002; Almasri & Kaluarachchi, 2004; Gardner & Vogel, 2005; Chen et al., 2010; Kulongoski & Belitz, 2011). While there are a number of natural sources of nitrate to groundwater, agricultural land uses are often identified as primary nitrate sources because humans have the most influence over the introduction and management of nitrogen sources at the surface (Power & Scheppers, 1989).

Land use activities determine the type and amount of contaminants introduced at the surface (Gardner & Vogel, 2005). Agricultural activities are a diffuse source of pollution, as they are spread across a large area. Because contamination is introduced over a wide area and infiltrates across this space, large quantities of contamination can be accumulated and stored across the underlying aquifer (Lerner & Harris, 2009).

In heavily agricultural areas, overuse of soils can alter the physical and hydrogeologic properties of the soils (Secunda et al., 1998). Additionally, high levels of nitrate in irrigation water can lead to the loss of fertility in soils (McLay et al., 2001). This can then lead to degradation and loss of attenuation potential to remove nitrogen from soil and therefore, the potential for leaching of nitrate to groundwater is high (Almasri & Kaluarachchi, 2004). Leaching occurs when nitrogen applied exceeds both crop demand and the denitrification capacity of soils (Almasri & Kaluarachchi, 2004). Once nitrate has leached from soil, it will move with infiltrating water into the subsurface and may eventually reach the underlying aquifer. Extensive irrigation and nitrogen fertilizers generally combine to result in low nitrogen use efficiency and high nitrogen losses (Chen et al., 2010). As a result, excess nitrogen will be available for leaching with irrigation waters. Additionally, in some irrigated areas, soil flushing is necessary to remove accumulated salts. Irrigation water will always contain some salts, which will remain in the soil after water has been lost to evapotranspiration (Power & Scheppers, 1989). If nitrate is also present in soils, it will be flushed into the subsurface, along with other salts.

Nitrate is highly soluble and does not readily sorb to solid surfaces, such as soil, thus allowing nitrate to have a high mobility (Weiner, 2013). The mobility of nitrate makes it prone to leaching through the soil, as it moves with infiltrating water into the subsurface (Nolan et al., 2002). Because nitrate does not form insoluble precipitates or absorb to solid surfaces, reduction is the only way to remove nitrate from groundwater (Appelo & Postma, 2013). Denitrification, the name given to the process for the reduction of nitrate, requires specific conditions to occur, including the presence of dissolved nitrate, organic carbon, denitrifying bacteria, and reducing conditions (DO (dissolved oxygen) < 0.5 mg/L) (Weiner, 2013). Nitrate is highly stable in oxic groundwater, but may be reduced into non-toxic forms under anoxic conditions (Tesoriero & Voss, 1997). The high solubility and mobility of nitrate, combined with the slim likelihood for natural attenuation, makes nitrate contamination extremely difficult and expensive to remediate.

The travel time for nitrate entering the subsurface to the point of discharge is often on the scale of years to centuries, depending on aquifer characteristics (Lerner & Harris, 2009). Once nitrate has infiltrated into the subsurface, its high mobility and unlikelihood to attenuate makes nitrate difficult to remediate, and contamination issues can persist for many years, or even decades. Even if comprehensive management practices were implemented in a basin, the existing contamination issues would persist for a long period of time.

In order to evaluate the potential for groundwater pollution, groundwater vulnerability assessments are commonly performed. Groundwater vulnerability assessments do not model current contamination, but rather assess the potential that an area may become contaminated (Kumar et al., 2016). Vulnerability is a relative, dimensionless property that cannot be directly measured (Piscopo, 2001).

There are two types of groundwater vulnerability: intrinsic and specific. Intrinsic vulnerability refers to the vulnerability of an aquifer to pollution based on physical hydrogeologic characteristics of the aquifer and does not include the potential impact of attenuation processes (Jamrah et al., 2008). In contrast, specific vulnerability includes pollutant properties and anthropogenic activities in combination with those physical aquifer characteristics (Srinivasamoorthy et al., 2011). To determine specific vulnerability, the intrinsic vulnerability of an aquifer is combined with the risk of pollution from specific sources, such as agricultural activities (Babiker et al., 2005). Many studies have found specific vulnerability assessments to improve the accuracy of pollution potential models (Secunda et al., 1998; Rupert, 2001; Babiker et al., 2005; Panagopoulos et al., 2006; Akhavan et al., 2011; Sadat-Noori & Ebrahimi, 2016).

Three categories exist for evaluating groundwater vulnerability: process-based simulation models, statistical methods, and overlay-index methods (Javadi et al., 2011). Process-based models use mathematical models to simulate the behavior of contaminants in the subsurface (Remesan and Panda, 2008). Statistical methods use statistics to determine the relationship between spatial variables and the occurrence of contaminants in the subsurface (Babiker et al., 2005). Overlay-index methods combine the influence of factors controlling the movement of contaminants from the surface into an aquifer (Srinivasamoorthy et al., 2011). Overlay-index methods are the preferred method as the data required is available over large areas, resulting in regional scale analyses (Yin et al., 2013). With all three categories, the accuracy of a groundwater vulnerability assessment is dependent upon the amount and quality of data (Piscopo, 2001).

Because groundwater is such an important freshwater resource, the protection of groundwater quality is crucial for water resources management. Groundwater vulnerability assessments are an especially valuable tool as they allow for prevention of future groundwater quality deterioration, evaluation of economic impacts of management decisions, and inform decision making, including resource management, land use changes, and establishment of monitoring networks (Sener et al., 2009).

The purpose of this research is to develop a groundwater vulnerability map for nitrate contamination in the Salinas Valley, a predominately agricultural groundwater basin in Coastal California. This assessment can then be used to inform management decisions and target areas for nitrate management programs.

2. BACKGROUND

2.1. Salinas Valley

The Salinas Valley Groundwater Basin, shown in **Figure 2-1**, is the largest coastal aquifer in California, located in the Coast Ranges between the San Joaquin Valley and the Pacific Ocean in central California. Spanning parts of Monterey and San Luis Obispo counties, the Basin is overlain by approximately 994,700 acres of land and includes nine hydrogeologically connected subbasins. The Salinas River drains the Basin, running 150 miles south to north through the center of the Valley from its headwaters to mouth at Monterey Bay (Planert & Williams, 1995). The Salinas Valley is bounded by the La Panza Range to the south, Santa Lucia Range to the southwest, Sierra de Salinas to the northwest, and the Diablo and Gabilan Ranges to the northeast (Planert & Williams, 1995).

Figure 2-1. Location map of the Salinas Valley Groundwater Basin.

The Salinas Valley Basin has a Mediterranean climate consisting of mild summers and cool winters. Mean annual precipitation ranges from 10-15 inches in the valley to 15-60 inches in the mountains, with 87% of rainfall occurring from November to April (RMC & LSCE, 2006).

According to the 2010 U.S. Census, the population of Monterey County was 415,057. Mean annual household income was $58.763, and 15.3% of the population was below poverty line (U.S. Census Bureau, 2017). The highest employment sector within the county is agriculture or support for agricultural activities (Kerna et al., 2009).

Major land uses within the Salinas Valley include agriculture, rangeland, forest, and urban development. The Salinas Valley has been an agricultural center for over 100 years (Moran et al., 2011). Agriculture is an almost three billion dollar per year industry in the Salinas Valley, which ranks fourth in the United States for total agricultural production (USDA, 2012). The majority of agriculture activity occurs in the northern two-thirds of the Valley, with vegetables being the primary crop (RMC & LSCE, 2006). In the lower third of the Valley, there is much less agricultural activity, with the primary crops being grains and wine grapes (RMC & LSCE, 2006). The Salinas Valley ranks first nationally in vegetable, melon, potato, and sweet potato production, sixth nationally in fruit, tree nut, and berry production, and ninth nationally in nursery, greenhouse, floriculture, and sod production (USDA, 2012).

2.2. Groundwater Use

Groundwater is the source of almost all agricultural and municipal water supplies in the Salinas Valley. On average, groundwater provides 99% of total water supply in Monterey County and 92% of total water supply in San Luis Obispo County (Martin, 2014). Additional water supplies include a very small amount of surface water from Arroyo Seco to supplement drinking water supply and recycled water to supplement agricultural irrigation supply (RMC & LSCE, 2006).

Agriculture is the largest water user in the Salinas Valley (RMC & LSCE, 2006). Since the 1980s, total irrigated acreage has remained relatively constant while urban acreage has continued to grow (RMC & LSCE, 2006). Due to changes in crop patterns, better irrigation management, and the development of recycled water as an additional irrigation supply, agricultural groundwater use has been on the decline (Brown and Caldwell, 2015). Meanwhile, urban groundwater use has increased with increasing urban development (Brown and Caldwell, 2015).

The major issues affecting the Salinas Valley Groundwater Basin are overdraft, seawater intrusion, and nitrate contamination (Moran et al., 2011). Overdraft occurs when groundwater is being pumped at a higher rate than recharge is occurring, resulting in a lowering of the water table and depletion of groundwater supplies. Seawater intrusion, which affects the northern most portion of the Basin, is a result of this overdraft. Because of seawater intrusion problems, urban and agricultural wells in the area have been abandoned (RMC, 2006). Nitrate problems are present across the entire basin, with measurements above the MCL recorded in all subbasins, but the intensity of contamination varies spatially (HydroFocus, Inc., 2014).

Nitrate contamination was first reported within the Salinas Valley Basin in 1978 (RMC, 2006). Since that time, the State Water Resources Control Board (SWRCB) has twice documented that nitrate levels within the Basin have impaired the beneficial use of groundwater for drinking water supply, first in 1988 and next in 1992 (RMC, 2006). In 1995, the SWRCB listed the Salinas Valley as the Basin with the highest water quality concern in California due to the severity of nitrate contamination issues (RMC, 2006). Most recently, all nine subbasins of the Salinas Valley Groundwater Basin were identified as “medium” or “high” priority in the final CASGEM Groundwater Basin Prioritization report due to nitrate, overdraft, and seawater intrusion problems (Martin, 2014).

A background nitrate concentration of 1.21 mg/L has been observed in groundwater, derived from rain and minor natural inputs from soils (Moran et al., 2011). Anthropogenic sources of nitrate within the Basin include agricultural practices, animal containment facilities, sewage treatment facilities, individual septic systems, municipal and industrial runoff (RMC & LSCE, 2006). A significant positive correlation between agricultural land use and nitrate contamination within the Basin has been observed, suggesting that the nitrate contamination issues are related to agricultural activities (Kulongoski & Belitz, 2011).

Groundwater withdrawals occur primarily from the 180-foot and 400-foot aquifers in the northern portion and unconfined aquifer in the southern portion of the Basin (RMC, 2006), with 84% of domestic wells screened within 400 feet of the land surface (HydroFocus, Inc., 2014).

Nitrate contamination has been observed at higher concentrations primarily in the shallow zone (Kulongoski & Belitz, 2011). As a result, nitrate contamination in the Salinas Valley poses a serious risk to drinking water supplies.

Nitrate concentrations have significantly increased over the last half-century, with travel time from source to detection in wells ranging from years to decades in domestic wells to years to many decades in deeper wells (Harter et al., 2012). As past contamination continues to move through the subsurface and enter the aquifer, nitrate problems will continue to worsen for years to come (Harter et al., 2012). While nitrate problems will persist for an extended time, management at the surface will reduce further damage to groundwater supplies and prevent irreparable damage to groundwater quality.

2.3. Hydrogeologic Setting

The Salinas Valley Groundwater Basin is a structural trough bounded by igneous and metamorphic rocks of pre-Tertiary age (Planert & Williams, 1995). The water bearing geologic formations comprising the aquifer of the Salinas Valley include undifferentiated basin deposits of Pleistocene to recent age, Pleistocene Aromas Red Sands, Plio-Pleistocene Paso Robles Formation, and Pliocene Purisma Formation (Brown and Caldwell, 2015).

The Pliocene Purisma Formation has a maximum thickness of 1,200 feet and includes marine sandstone, conglomerate, and mudstone (Durbin et al., 1978). The Pleistocene Paso Robles Formation has a maximum thickness of 2,000 feet includes unconsolidated to consolidated gravel, sand, and silt (Durbin et al., 1978). The Pleistocene Aromas Red Sands include mainly cross-bedded sand with some clayey layers and has a distinct red or brownish color (RMC & LSCE, 2006). The undifferentiated basin deposits include Valley Fill overlain by 10 to 75 feet of Recent Alluvium (RMC & LSCE, 2006). The Valley Fill ranges from 25 to 100 feet in thickness and includes alternating interconnected, complex beds of fine-grained and coarser-grained estuarine and fluvial deposits (RMC & LSCE, 2006). The Recent Alluvium, derived from the Salinas River, is of low to moderate permeability and located in the more established drainages of the Basin (RMC & LSCE, 2006).

Primary sources of recharge are infiltration from the Salinas River and infiltration of irrigation waters. Additional sources of recharge include precipitation, subsurface and boundary inflow, and seawater intrusion (HydroFocus, Inc., 2014). However, because irrigation waters are derived from groundwater, it is considered a recycling of water supplies, rather than a new inflow of water into the system (Salinas Valley Ground Water Basin Hydrology Conference, 1995).

2.4. Subbasins

The Salinas Valley Groundwater Basins consists of nine hydrogeologically connected subbasins, shown in **Figure 2-2**. The subareas are differentiated primarily by differences in confining conditions, specific capacity of wells, and sources of recharge (HydroFocus, Inc., 2014).

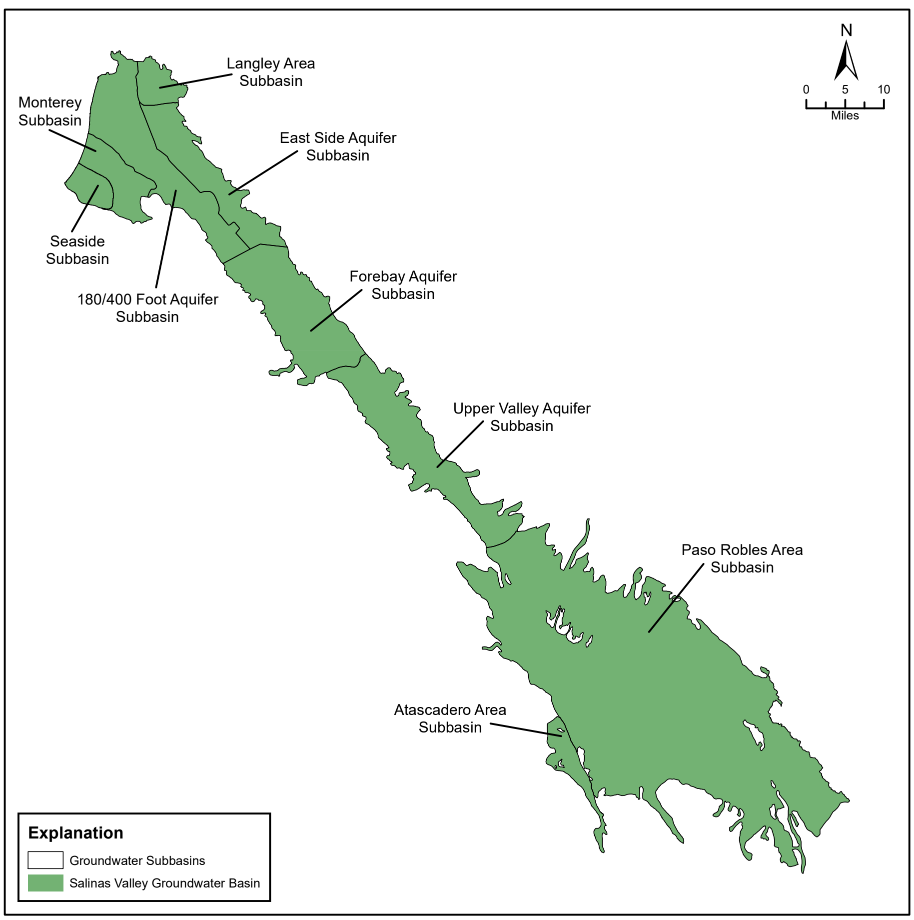

Figure 2-2. Subbasins of the Salinas Valley Groundwater Basin.

Modifications were made to the Salinas Valley Groundwater Basin according the 2016 update of the California (CA) Department of Water Resources (DWR) Bulletin 118. In the northwest, the Monterey and Seaside Aquifers were modified from the previous Seaside Area and Corral de Tierra Area Aquifers (CA DWR-B, 2016). Additionally, the Atascadero Area Aquifer in the southwest was made its own subbasin, after previously being a part of the Paso Robles Area Aquifer (CA DWR-B, 2016).

The Seaside Subbasin is located in the northwestern portion of the Salinas Valley Groundwater Basin and overlain by approximately 14,489 acres of land (**Figure 2-2**). Groundwater in the subbasin is unconfined and found in the Paso Robles Formation (CA DWR-A, 2004; CA DWR-B, 2004). According to the 2016 Bulletin 118 basin boundary modifications, the Seaside and Monterey Subbasins are separated by an unspecified groundwater divide (CA DWR-A, 2016). Seawater intrusion is the primary groundwater quality concern in the subbasin (CA DWR-B, 2004).

The Monterey Subbasin is located in the northwestern portion of the Salinas Valley Groundwater Basin and overlain by approximately 30,855 acres of land (**Figure 2-2**). Groundwater in the subbasin is unconfined and found in the Paso Robles Formation (CA DWR-A, 2004; CA DWR-B, 2004). According to the 2016 Bulletin 118 basin boundary modifications, the Seaside and Monterey Subbasins are separated by an unspecified groundwater divide (CA DWR-A, 2016). Seawater intrusion is the primary groundwater quality concern in the subbasin (CA DWR-B, 2004).

The 180/400-Foot Aquifer Subbasin is located in the northern portion of the Salinas Valley Groundwater Basin and overlain by approximately 89,706 acres of land (**Figure 2-2**). The 180/400-Foot Aquifer Subbasin has two primary aquifers: the 180-Foot aquifer and the 400-Foot aquifer. A third aquifer, the 900-Foot Aquifer, exists as well, but is currently undeveloped for groundwater use (CA DWR-C, 2004). Unique to this subbasin is the presence of the Salinas Aquitard, a confining blue clay layer ranging in thickness from 25 to 100 feet, overlying the 180-Foot aquifer (CA DWR-C, 2004). Groundwater in the 180-Foot aquifer is confined and found in unconsolidated terrace deposits and the Aromas Red Sands (CA DWR-C, 2004). Groundwater in the 400-Foot aquifer is confined and found in the Aromas Red Sands in the upper portion of the aquifer and Paso Robles Formation in the lower portion of the aquifer (CA DWR-C, 2004).

Because of the presence of the Salinas Aquitard, recharge from the surface is essentially zero and is provided by subsurface horizontal flow (CA DWR-C, 2004). Seawater intrusion is a significant water quality problem in this subbasin, as well as non-point source nitrate contamination (CA DWR-C, 2004). However, nitrate concentrations are generally lower in this subbasin due to the confining conditions (RMC & LSCE, 2006).

The Langley Area Subbasin is located in the northeastern portion of the Salinas Valley Groundwater Basin and overlain by approximately 17,605 acres of land (**Figure 2-2**). The primary water-bearing unit in the subbasin is the Aromas Red Sands (CA DWR-D, 2004). A series of confining layers occurs between the upper and lower Aromas Sands, resulting in an unconfined upper aquifer and confined lower aquifer (CA DWR-D, 2004). The lower aquifer is generally not used for groundwater supply (CA DWR-D, 2004). Elevated nitrate concentrations have been observed in the shallow areas of the unconfined aquifer (CA DWR-D, 2004).

The East Side Aquifer Subbasin is located in the northeastern portion of the Salinas Valley Groundwater Basin and overlain by approximately 57,475 acres of land (**Figure 2-2**). Groundwater is found in the same units as the 180/400-Foot Aquifer Subbasin, however no confining layer exists above the 180-Foot aquifer (CA DWR-E, 2004). Groundwater in the 180-Foot aquifer, also referred to as the shallow zone, is unconfined and found in unconsolidated terrace deposits and the Aromas Red Sands (CA DWR-E, 2004). Discontinuous sands and blue clays, ranging in thickness from 10 to 70 feet, separate the 180-Foot aquifer from the 400-Foot aquifer (CA DWR-E, 2004). Groundwater in the 400-Foot aquifer, also referred to as the deep zone, is unconfined and found in the Aromas Red Sands in the upper portion of the aquifer and Paso Robles Formation in the lower portion of the aquifer (CA DWR-E, 2004). Extensive nitrate contamination problems exist across the subbasin, likely due to long-term agricultural production on the surface (CA DWR-E, 2004).

The Forebay Aquifer Subbasin is located in the central portion of the Salinas Valley Groundwater Basin and overlain by approximately 94,052 acres of land (**Figure 2-2**). Groundwater is found in the same units as the 180/400-Foot Aquifer Subbasin, however no confining layer exists above the 180-Foot aquifer (CA DWR-F, 2004). Groundwater in the 180-Foot aquifer, also referred to as the shallow zone, is unconfined and found in unconsolidated terrace deposits and the Aromas Red Sands (CA DWR-F, 2004). Discontinuous sands and blue clays, ranging in thickness from 10 to 70 feet, separate the 180-Foot aquifer from the 400-Foot aquifer (CA DWR-F, 2004). Groundwater in the 400-Foot aquifer, also referred to as the deep zone, is unconfined and found in the Aromas Red Sands in the upper portion of the aquifer and Paso Robles Formation in the lower portion of the aquifer (CA DWR-F, 2004). Extensive nitrate contamination problems exist across the subbasin, likely due to long-term agricultural production on the surface (CA DWR-F, 2004).

The Upper Valley Aquifer Subbasin is located in the central portion of the Salinas Valley Groundwater Basin and overlain by approximately 98,171 acres of land (**Figure 2-2**). Groundwater in the subbasin is unconfined and found in unconsolidated to semi-consolidated sand, silt, and gravel deposits and the Paso Robles Formation (CA DWR-G, 2004). This unit is laterally equivalent to the 180-Foot and 400-Foot aquifers, but no aquitards exist to separate the zones (CA DWR-G, 2004). Extensive nitrate contamination problems exist across the subbasin, likely due to long-term agricultural production on the surface (CA DWR-G, 2004).

The Paso Robles Area Subbasin is the southern portion of the Salinas Valley Groundwater Basin and overlain by approximately 577,349 acres of land (**Figure 2-2**). Groundwater is found in Holocene age alluvium and the Pleistocene age Paso Robles Formation (CA DWR-H, 2004). The Paso Robles Subbasin has two main aquifers: an unconfined upper aquifer consisting primarily of alluvium and a confined lower aquifer consisting primarily of the Paso Robles Formation (CA DWR-H, 2004). Nitrate concentrations have been increasing in localized areas within the subbasin (CA DWR-H, 2004).

The Atascadero Area Subbasin is located in the southwestern portion of the Salinas Valley Groundwater Basin and overlain by approximately 19,735 acres of land (**Figure 2-2**). Previously considered to be a part of the Paso Robles Subbasin, the Atascadero Area was designated as its own subbasin according to the 2016 Bulletin 118 basin boundary modifications (CA DWR-B, 2016). The Atascadero Area Subbasin has two main aquifers: an unconfined upper aquifer consisting primarily of alluvium and a confined lower aquifer consisting primarily of the Atascadero Area Formation (CA DWR-H, 2004). While the subbasins share many hydrogeologic characteristics, groundwater flow between the subbasins is restricted due to a leaky barrier created by the Rinconada fault zone (CA DWR-H, 2004).

2.5 Previous Nitrate Studies in the Salinas Valley

Previous studies have assessed the occurrence and distribution of nitrate within the Salinas Valley Groundwater Basin. Common trends observed across previous studies include: (1) nitrate contamination is most common in shallow wells; (2) nitrate concentrations vary spatially; (3) nitrate contamination is related to agricultural activities; and (4) nitrate concentrations have been increasing with time.

Approximately 80-84% of the domestic wells within the Salinas Valley are screened within 400 feet of the ground surface (HydroFocus, Inc., 2014; LSCE, 2015). Higher concentrations of nitrate in groundwater generally occur in shallow wells (screened within 350 feet below ground surface (bgs)) of modern or mixed aged waters (Kulongoski and Belitz, 2011). Additionally, nitrate concentrations have been observed to vary spatially and generally decrease with depth (Boyle et al., 2012; HydroFocus, Inc., 2014; LSCE, 2015). In general, the largest percentages of groundwater nitrate MCL exceedances occur in the northern, eastern, and central Salinas Valley (Boyle et al., 2012).

A 2005 CA GAMA (Groundwater Ambient Monitoring and Assessment Program) Priority Basin Project found a significant positive correlation between nitrate in groundwater and agricultural land use on the surface (Kulongoski and Belitz, 2011). Geochemical and isotopic testing used in a 2011 CA GAMA Special Study confirmed that irrigated agriculture is the primary source of nitrate to groundwater (Moran et al., 2011).

A number of studies have observed the occurrence of nitrate within the Salinas Valley Groundwater Basin and an increasing trend in nitrate concentrations has been observed through time. Boyle et al. (2012) observed average nitrate concentrations in public supply wells to have increased approximately 2.5 mg/L per decade for the past three decades. The results of other studies that have observed the distribution and occurrence of nitrate in both domestic and public supply wells are presented in **Table 2-1**. An increase in mean nitrate and percentage of wells over the MCL is observed between 2001 and 2015. It should be noted that different wells and different quantities of wells were used in each study. As a result, the spatial variability of nitrate is also observed, as the HydroFocus, Inc. (2014) study shows a decrease in nitrate concentrations, which is likely due to different sampling patterns rather than a true decrease in concentrations.

Table 2-1. Summary of Nitrate Distribution and Occurrence Studies in the Salinas Valley.

Source	Year	Number of Wells	Mean Nitrate (mg/L)	Percent of Wells over the MCL
RMC & LSCE, 2006	2001	349	47	34%
Goldrath et al., 2014	2013	70*	-	34%
HydroFocus, Inc., 2014	2014	838	36.44	21%
LSCE, 2015	2015	758	68	41%

* Only shallow wells included in this study

2.6. Target Zone for Groundwater Vulnerability Assessment

The target zone selected for this analysis is the upper aquifer consisting of the 180-Foot aquifer in the northern portion of the Basin and upper aquifer in the southern portion. This zone was selected for analysis as most of the nitrate contamination problems in the Salinas Valley occur in the shallow zone. Additionally, this zone is the primary source of drinking water supply in the Salinas Valley Groundwater Basin.

3. METHODS

3.1. DRASTIC model

A groundwater vulnerability assessment will be conducted using the DRASTIC overlay-index method developed by the U.S. EPA. The DRASTIC model is a rank-sum method based on seven hydrogeologic parameters: **D**epth to Water, Net **R**echarge, **A**quifer media, **S**oil media, **T**opography (Slope), **I**mpact of the Vadose Zone, and Hydraulic **C**onductivity (Aller et al., 1987).

Each parameter includes a range of values, obtained from data, which influence pollution potential. The values within this range are then given a ranking based on the impact of each value to pollution potential with respect to the other values (see **Table 3-2** for example). Rankings range from 1 (least impactful) to 10 (most impactful). Parameters are also given a weight (shown in **Table 3-1**) based on the overall significance of that parameter to the final vulnerability calculation, relative to the other parameters. Weights range from 1 (least significant) to 5 (most significant).

Table 3-1. Weights assigned to DRASTIC parameters (Aller et al., 1987).

Parameter	Weight
Depth to Water	5
Net Recharge	4
Aquifer Media	3
Soil Media	2
Topography (slope)	1
Impact of Vadose Zone	5
Hydraulic Conductivity	3

The overall DRASTIC vulnerability index (DVI) is calculated using Equation 1 (Aller et al., 1987):

$$DVI = D_wD_r + R_wR_r + A_wA_r + S_wS_r + T_wT_r + I_wI_r + C_wC_r \qquad \text{eqn. 1}$$

In this equation, each hydrogeologic parameter is represented by a letter (D, R, A, S, T, I, C), and rankings and weights are designated by *r* and *w*, respectively. Values for DVI can range from 23 to 226, with a higher DVI indicating higher pollution potential. The meaning of DVI values are specific to each unique assessment and cannot be used to compare results across different studies (Aller et al., 1987).

To classify map units with high, moderate, low, or very low pollution potential, the range of DVI values calculated can be divided into four ranges (Srinivasamoorthy et al., 2011). In this assessment, the ranges were determined using equal intervals. Thus, the lowest interval would have very low pollution potential while the highest interval would have high pollution potential.

The DRASTIC model relies on four assumptions: (1) the contaminant is introduced at the ground surface; (2) the contaminant is flushed into groundwater by precipitation; (3) the contaminant has the mobility of water; and (4) the area evaluated is greater than or equal to 100 acres (Aller et al., 1987). The Salinas Valley Groundwater Basin qualifies for DRASTIC analysis under these assumptions. The Basin is overlain by approximately 999,437 acres of land on the surface. Nitrate, the contaminant of interest in this assessment, is highly soluble and is introduced at the surface primarily through agricultural activity, but also from a number of urban sources. Finally, while precipitation is a source of recharge within the Salinas Valley Basin, the primary source of recharge is irrigation waters. This recharge pathway is accounted for within the model modifications used in this study.

Aller et al. (1987) posit that the DRASTIC parameters can be used to represent vulnerability in terms of travel time, flux, and concentration. Travel time refers to the amount of time it takes for the contaminant to move from source to detection. In this case, travel time is represented by depth to water, net recharge, soil media, impact of the vadose zone, and hydraulic conductivity. Flux refers the flow rate per unit area, or how fast water moves through a given area. Flux is represented by aquifer media and hydraulic conductivity. Concentration refers to the amount of a contaminant present in groundwater. Concentration is represented by depth to water, net recharge, aquifer media, soil media, topography (slope), impact of the vadose zone, and hydraulic conductivity.

The DRASTIC model is popular as it is easy to use and utilizes common, often publicly available, data (Sadat-Noori & Ebrahimi, 2016). Additionally, the DRASTIC model is suitable for basin-scale analysis, rather than other site-specific models (Colins et al., 2016). However, there are drawbacks to the DRASTIC model. The primary drawback to DRASTIC is that it does not consider a specific pollutant, but rather evaluates intrinsic vulnerability only. In addition, DRASTIC does not account for attenuation processes (Srinivasamoorthy et al., 2011). Plus, the model does not incorporate flow and transport processes within the groundwater basin (Kumar et al., 2016).

3.2. Confining Aquifer Modifications

The 180/400-Foot aquifer subbasin is a confined aquifer and must be evaluated differently from the rest of the Salinas Valley Groundwater Basin. The DRASTIC model was designed to evaluate pollution potential in unconfined aquifers. However, modifications were also developed to evaluate confined aquifers. The presence of a confining layer will deter contaminants from entering the aquifer, thus a confined aquifer will have a lower DVI (Aller et al., 1987). The parameters to be modified under confining conditions are depth to water, net recharge, and impact of the vadose zone.

3.3. Modifications to DRASTIC model

The original DRASTIC model does not consider contamination by a specific pollutant; rather, it indicates vulnerability to groundwater pollution in general. For the purpose of this analysis, the DRASTIC model will be modified to determine groundwater specific vulnerability to nitrate pollution. Previous studies have included a land use parameter to represent a specific contaminant, such as nitrate, (Secunda et al., 1998; Samara & Yoxas, 2013), while other studies have modified parameter rankings based on measured concentrations data (Panagopoulos et al., 2006; Javadi et al., 2011). In some cases, both methods have been applied, and resulted in statistically significant improvements to the groundwater vulnerability assessment (Akhavan et al., 2011; Sadat-Noori & Ebrahimi, 2016). In this study, due to data limitations and project constraints, it was not possible to modify rankings based on measured nitrate concentrations data.

In this analysis, a land use parameter will be added to modify the DRASTIC model, and will be used to represent groundwater specific vulnerability to nitrate contamination. Because agricultural activities have been shown to be a primary cause of nitrate contamination in the Salinas Valley (Kulongoski & Belitz, 2011; Moran et al., 2011), land use can be used as an indicator of potential nitrate contamination in the Basin. Additionally, because agriculture is the largest water user in the Salinas Valley, the land use parameter can also account for the recharge impacts of agricultural irrigation. Secunda et al. (1998) presented a method for modifying the DRASTIC model to incorporate a land use parameter. Based on this method, the land use parameter is assigned a weight of five and the modified DVI is calculated according to Equation 2 (Secunda et al., 1998):

$$\text{modified DVI} = \text{DVI} + L_w L_r \qquad \text{eqn. 2}$$

3.4. Parameters

3.4.1. Depth to Water

The depth to water parameter represents the depth to the water table from the ground surface. In general, as depth to water increases, pollution potential decreases (Aller et al., 1987). Because a contaminant must travel further through the vadose zone to reach a deeper water table, there is more time for, and a greater chance of, attenuation.

Depth to water data was acquired from the CA DWR Water Data Library, U.S. Geological Survey (USGS) National Water Information System (NWIS), and Geotracker-GAMA. Wells were selected for use if adequate construction details were available to verify the measured water level is indicative of the target aquifer zone. Wells chosen for analysis had perforations less than 350 feet bgs, or a total well depth of less than 350 feet bgs. Water level values were selected from the 2016 water year (October 2015 through September 2016) and the minimum depth to water value recorded during that time period was used for analysis.

Wells with depth to water values were plotted as point features in ArcGIS. Using the Spatial Analyst extension, a depth to water surface was created using the Inverse Distance Weighted (IDW) interpolation method. The values of the resulting depth to water raster were then classified based on the DRASTIC rankings provided in **Table 3-2**.

Under confining conditions, the depth to water parameter is defined as the base of the confining layer, or top of the aquifer (Aller et al., 1987). The confining layer within the 180/400-foot Aquifer, known as the Salinas Aquitard, ranges in thickness from 25 feet near Salinas to greater than 100 feet near Monterey Bay (CA DWR-C, 2004). For the purpose of this study, the depth to the bottom of the Salinas Aquitard confining unit was considered to be 180 feet bgs across the entire subbasin. The depth to water parameter was therefore assigned a ranking of one in this subbasin, according to the rankings shown in **Table 3-2**.

Table 3-2. Rankings assigned to Depth to Water parameter (from Aller et al., 1987).

Depth to Water (ft)	
Range	***Ranking***
0-5	10
5-15	9
15-30	7
30-50	5
50-75	3
75-100	2
100+	1

3.4.2. Net Recharge

The net recharge parameter refers to the amount of water that enters the subsurface and eventually reaches the water table. Recharge water is the primary way in which contaminants are transported, both vertically and horizontally, through the subsurface. Generally, more recharge increases the potential for contamination to enter the groundwater.

Data needed for the determination of net recharge included topographic slope, rainfall, and soil permeability. Topographic slope data was obtained from the USGS National Elevation Dataset (NED). Data processing for this parameter is explained in the Topography (Slope) section. Rainfall data was obtained from the PRISM Climate Group in the form of a 30-year normal precipitation raster. Soil permeability data was obtained from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO) in raster format. Soil permeability ranges were determined based on the saturated hydraulic conductivity (Ksat) for the key horizon within the major soil component of each map unit. Key horizons were identified as the layer most restrictive to flow within the soil component. Soil permeability classes were then determined from Ksat values according to the ranges shown in **Table 3-3**.

Table 3-3. Permeability Classes based on Saturated Hydraulic Conductivity (Ksat) values (adapted from NRCS, 2014).

Permeability Class	Ksat (μm/sec)
Very Rapid	141-705
Rapid	42-141
Moderately Rapid	14-42
Moderate	4-14
Moderately Slow	1.4-4
Slow	0.42-1.4
Very Slow	0.01-0.42
Impermeable	0.0-0.01

Table 3-4. Rankings assigned to Net Recharge components and parameter (from Piscopo, 2001).

Net Recharge							
Slope (%)		**Rainfall (mm)**		**Soil Permeability**		**Recharge**	
Range	***Ranking***	***Range***	***Ranking***	***Range***	***Ranking***	***Range***	***Ranking***
< 2	4	> 850	4	High	5	11-13	10
2-10	3	700-850	3	Mod-high	4	9-11	8
10-33	2	500-700	2	Moderate	3	7-9	5
> 33	1	<500	1	Slow	2	5-7	3
				Very slow	1	3-5	1

Each component was assigned rankings, as shown in **Table 3-4**, and net recharge was calculated according to Equation 3 (Piscopo, 2001):

$$\text{Recharge value} = \text{Slope} + \text{Rainfall} + \text{Soil permeability} \qquad \text{eqn. 3}$$

The calculated recharge value was then assigned rankings, as shown in **Table 3-4**.

Under confining conditions, the net recharge parameter must be adjusted to reflect the barrier to recharge of the confining layer. With the presence of a confining layer, sources of recharge into the confined aquifer are often miles away (Aller et al., 1987). While semi-confined, or leaky, aquifers may allow some recharge through the confining layer, truly confined aquifers do not. The 180/400-Foot aquifer subbasin is a truly confined aquifer, as the Salinas Aquitard is impermeable, and recharge is considered neglible (CA DWR-C, 2004). The net recharge parameter was assigned a ranking of one in this subbasin.

3.4.3. Aquifer Media

The aquifer media parameter represents the geologic material that makes up the saturated aquifer zone. Aquifer media influences the flow and transport properties of the aquifer. Thus, this parameter represents how quickly water and contaminants move through the aquifer and the time available for attenuation processes to occur. Aquifer media attempts to account for the porosity of geologic materials, whereas the Hydraulic Conductivity parameter simply addresses the travel time of a contaminant in the subsurface. Generally, coarser grained media or media with more fractures allow for water to move more quickly (Aller et al., 1987). As a result, there is less time for attenuation to occur and a greater potential for pollution.

Aquifer media data was obtained from geologic maps. Digital copies of 1:250,000 scale maps for the Santa Cruz quadrangle (Jennings & Strand, 1958) and San Luis Obispo quadrangle (Jennings, 1958) were georeferenced and digitized within ArcGIS. Lithology descriptions were obtained from a literature review (Wilmarth, 1931; Durham, 1974) and rankings were assigned to the mapped lithologies as shown in **Table 3-5**.

Table 3-5. Rankings assigned to Aquifer Media parameter.

Aquifer Media			
Geologic Unit	**Geologic Unit Description (Wilmarth, 1931; Durham, 1974)**	**DRASTIC Category**	**Ranking (Aller et al., 1987)**
gr, Mesozoic granitic rocks	Igneous and Metamorphic Rocks	Metamorphic/ Igneous Rock	3
m, Pre-Cretaceous metamorphic rocks	Igneous and Metamorphic Rocks	Metamorphic/ Igneous Rock	3
ub, Mesozoic ultrabasic intrusive rocks	Igneous and Metamorphic Rocks	Metamorphic/ Igneous Rock	3
Mm, Middle Miocene marine	Mudstone/Sandstone	Bedded Sandstone, Limestone, and Shale	6

Mu, Upper Miocene marine	Shale and Sandstone	Bedded Sandstone, Limestone, and Shale	6
Pml, Middle and/or lower Pliocene nonmarine	Sandstone	Bedded Sandstone, Limestone, and Shale	6
KI, Lower Cretaceous marine	Sandstone	Bedded Sandstone, Limestone, and Shale	6
Oc, Oligocene nonmarine	Conglomerate/ Conglomerate Sandstone	Sand and Gravel	6
Pc, Undivided Pliocene nonmarine	Silt/sand/gravel and Sandstone	Sand and Gravel	7
QP, Plio-Pleistocene nonmarine	Sand and Gravel	Sand and Gravel	8
Qc, Pleistocene nonmarine	Sand and Gravel	Sand and Gravel	8
Ql, Quaternary lake deposits	Sand	Sand and Gravel	8
Qs, Sand dunes	Sand	Sand and Gravel	8
Qf, Fan deposits	Sand	Sand and Gravel	8
Qal, Alluvium	Sand and Gravel	Sand and Gravel	9
Qt, River terrace deposits	Gravels	Sand and Gravel	9

3.4.4. Soil Media

The soil media parameter refers to the material at the ground surface down to approximately seven feet bgs. The compositions of soils determine the amount of recharge that will move from the surface into the subsurface, and thus the likelihood of a contaminant entering the subsurface. The presence of a clay layer within a soil horizon will restrict the amount of recharge moving through the soil, while coarse-grained materials such as gravels and sands will facilitate the movement of water into the subsurface (Aller et al., 1987).

Soil media data was obtained from the NRCS SSURGO in raster format. Soil media was determined from the percentage of sand, silt, and clay within each horizon of the major component of each map unit. A single soil media type was then chosen by selecting the most restrictive soil media type, or layer which would be most restrictive to water flow, within each component. Soil media types were then assigned rankings, as shown in **Table 3-6**.

Table 3-6. Rankings assigned to Soil Media parameter (from Aller et al., 1987).

Soil Media	
Range	***Ranking***
Thin or Absent	10
Gravel	10
Sand	9
Peat	8
Shrinking and/or Aggregated Clay	7
Sandy Loam	6
Loam	5
Silty Loam	4
Clay Loam	3
Muck	2
Nonshrinking and Nonaggregated Clay	1

3.4.5. Topography (Slope)

The topography parameter represents the slope, or change in elevation over a fixed distance, of the land surface. The slope of the land surface will determine whether a contaminant will runoff or infiltrate. A higher slope suggests runoff and has a lower pollution potential, while a lower slope suggests a pollutant will remain in the same place for enough time to infiltrate and thus, has a greater pollution potential (Aller et al., 1987).

Topography data was obtained from the USGS NED in the form of a 1/3-arc second digital elevation models (DEMs). DEMs were obtained for the following latitude/longitude tiles encompassing the study area: N36W121, N36W122, N37W121, and N37W122. The DEMs were merged together into a single DEM using ArcGIS and then converted to percent slope using the Spatial Analyst extension. The slope values were then classified according to the rankings shown in **Table 3-7**.

Table 3-7. Rankings assigned to Topography (slope) parameter (from Aller et al., 1987).

Topography (% Slope)	
Range	***Ranking***
0-2	10
2-6	9
6-12	5
12-18	3
18+	1

3.4.6. Impact of the Vadose Zone

The impact of the vadose zone parameter represents the area between the ground surface and water table that is unsaturated or infrequently saturated. The vadose zone influences the likelihood of a contaminant traveling from the surface into groundwater. Various attenuation processes, including biodegradation, neutralization, mechanical filtration, chemical reaction, volatilization, and dispersion, occur in the vadose zone (Aller et al., 1987). Thus, similarly to depth to water, the composition of the vadose zone impacts the time it takes for a contaminant to move through the subsurface and can affect the time available for attenuation to occur. However, the inclusion of soil permeability addresses the way a contaminant moves through the subsurface. If soil permeability is high, the contaminant will move into the subsurface quickly. If soil permeability is low, the contaminant will move into the subsurface slowly, and may even be restricted from entering the subsurface at all.

Data needed for the determination of the impact of the vadose zone included soil permeability and depth to water. The soil permeability layer used in the net recharge calculation was also used for this calculation and ranked according to the same scheme shown in **Table 3-3**. The depth to water parameter previously created was also used for this calculation and was ranked according to the scheme shown in **Table 3-8**, in order to remain consistent with the method used to determine the impact of the vadose zone. The impact of the vadose zone was then calculated using Equation 4 (Piscopo, 2001):

$$\text{Impact of the Vadose Zone} = \text{Soil Permeability} + \text{Depth to Water} \qquad \text{eqn. 4}$$

The calculated impact of the vadose zone ranges were then assigned rankings, as shown in **Table 3-8**.

Under confining conditions, the impact of the vadose zone is dependent on the properties of the confining layer. The Salinas Aquitard is impermeable (CA DWR-C, 2004) and was assigned a permeability ranking of one. As previously stated, the depth to water parameter was also assigned a ranking of one. According to the calculation and rankings provided in equation 4 and **Table 3-8**, respectively, the impact of the vadose zone parameter was assigned a ranking of one in this subbasin.

Table 3-8. Rankings assigned to Impact of Vadose Zone parameter (from Piscopo, 2001).

Impact of the Vadose Zone					
Soil Permeability		**Depth to Water (ft)**		**Impact of the Vadose Zone**	
Range	***Ranking***	***Range***	***Ranking***	***Range***	***Ranking***
High	5	< 16.4	5	8-10	10
Mod-high	4	16.4-32.8	4	6-8	8
Moderate	3	32.8-49.2	3	4-6	5
Slow	2	49.2-65.6	2	3-4	3
Very slow	1	> 65.6	1	2-3	1

3.4.7. Hydraulic Conductivity

The hydraulic conductivity parameter represents the ease at which water is transmitted through the aquifer. The higher the hydraulic conductivity, the easier it is for water to move through the aquifer (Aller et al., 1987). As a result, a high hydraulic conductivity is associated with higher pollution potential, as contaminants can also move through the aquifer with greater ease.

Hydraulic conductivity values were derived from the lithologies identified in the Aquifer Media parameter. Representative hydraulic conductivity values, shown in **Table 3-9**, were chosen for each lithology and joined to the aquifer media parameter. The hydraulic conductivity ranges were then assigned rankings as shown in **Table 3-10**.

Table 3-9. Representative Hydraulic Conductivity (K) values assigned to geologic units (from Heath, 1983).

DRASTIC Category	Geology Type	Description	K (gpd/ft^2)
Bedded Sandstone, Limestone, and Shale	*Mu*, Upper Miocene marine	Shale and Sandstone	10^{-3}
	Mm, Middle Miocene marine	Mudstone/Sandstone	10^{-2}
	Pml, Middle and/or lower Pliocene nonmarine	Sandstone	$5x10^{-1}$
	KI, Lower Cretaceous marine	Sandstone	$5x10^{-1}$
Metamorphic/ Igneous Rock	*gr*, Mesozoic granitic rocks	Igenous and Metamorphic Rocks	10^{1}
	m, Pre-Cretaceous metamorphic rocks	Igenous and Metamorphic Rocks	10^{1}
	ub, Mesozoic ultrabasic intrusive rocks	Igenous and Metamorphic Rocks	10^{1}
Sand and Gravel	*Oc*, Oligocene nonmarine	Conglomerate/ Conglomerate Sandstone	10^{2}
	Pc, Undivided Pliocene nonmarine	Silt/sand/gravel and Sandstone	10^{2}
	Ql, Quaternary lake deposits	Sand	$5x10^{2}$
	Qs, Sand dunes	Sand	$5x10^{2}$
	Qf, Fan deposits	Sand	$5x10^{2}$
	QP, Plio-Pleistocene nonmarine	Sand and Gravel	$2x10^{3}$
	Qc, Pleistocene nonmarine	Sand and Gravel	$2x10^{3}$
	Qal, Alluvium	Sand and Gravel	$2x10^{3}$
	Qt, River terrace deposits	Gravels	10^{4}

Table 3-10. Rankings assigned to Hydraulic Conductivity parameter (from Aller et al., 1987).

Hydraulic Conductivity (gpd/ft2)	
Range	***Ranking***
1-100	1
100-300	2
300-700	4
700-1000	6
1000-2000	8
2000+	10

3.4.8. Land Use

The land use parameter represents the dominant land use on the ground surface. Land use practices, particularly in agriculturally dominated areas, have been shown to have a significant effect on groundwater quality (McLay et al., 2001; Almasri & Kaluarachchi, 2004; Almasri & Kaluarachchi, 2007). In the case of the Salinas Valley, agricultural land use practices have been positively correlated with the occurrence of nitrate in groundwater (Kulongoski & Belitz, 2011). Therefore, in this study, the land use parameter is added to represent potential nitrate contamination. Additionally, because agriculture is the largest water user in the Salinas Valley, land use can be used to account for the recharge derived from agricultural irrigation.

The development of a land use parameter has been adapted from Secunda et al. (1998). Data for the land use parameter was obtained from the U.S. Department of Agriculture (USDA) Cropland Data Layer (CDL) in raster format for the year 2016. The various land use categories mapped within the study area were then assigned rankings as shown in **Table 3-11**.

Table 3-11. Rankings assigned to Land Use parameter (from Secunda et al., 1998).

Land Use	
Category	**Ranking**
Cotton	10
Built-up areas	8
Irrigated field crops	8
Greenhouse/tomatoes	8
Reservoirs	7
Citrus Orchards	7
Orchards of other fruit	6
Pasture or other land unsuitable for agricultural use	5
Uncultivated land	5
Temporarily uncultivated land	5
Vineyards	5
Olives	5
Quarries	5
Non-irrigated field crops	4
Avocados	2
Forests	1
Natural areas or reserves	1
Dune sands - Open areas	1

3.5 Sensitivity Analysis

Two sensitivity tests were performed to evaluate the individual parameters used to determine the overall DVI: a map removal sensitivity analysis, as developed by Lodwick et al. (1990) and a single parameter sensitivity analysis, as developed by Napolitano and Fabbri (1996).

3.5.1. Map Removal Sensitivity Analysis

The map removal sensitivity analysis examines the sensitivity of the DVI due to the removal of one or more parameter maps. Two tests of the map removal sensitivity were performed in this study. The first test evaluates the variation of the DVI due to the removal of a single parameter map from the overall calculation. The second test evaluates the variation of the DVI due to the cumulative, one at a time, removal of parameter maps. The order in which parameter maps are removed is based on the single map removal test. The parameter maps contributing the least variation to the DVI are preferentially removed. The sensitivity of the map removal process is calculated according to equation 5:

$$S = ((|V/N - V'/n|) / V) * 100 \qquad \text{eqn. 5}$$

In this equation, S is the sensitivity measure expressed as the variation index, V is the unperturbed vulnerability index (original DVI calculation), V' is the perturbed vulnerability index (calculation of DVI after map removal), N is the number of parameters used in the determination of V, and n is the number of parameters used in the determination of V'.

3.5.2. Single Parameter Sensitivity Analysis

The single parameter sensitivity analysis examines the impact of each parameter to the overall DVI calculation. This test compares the "theoretical" weight assigned to each parameter by DRASTIC against the calculated "effective" weight. The "effective" weight compares the combined rankings and weight assigned by DRASTIC to a given parameter against the overall calculated DVI. The overall impact, or "effectiveness", to the DVI can then be determined by comparing the "effective" weights of each parameter. The "effective" weight of each parameter is calculated according to equation 6:

$$W = (P_r P_w / V) * 100 \qquad \text{eqn. 6}$$

In this equation, W is the "effective" weight of each parameter, P_r is the ranking assigned by DRASTIC, P_w is the weight assigned by DRASTIC, and V is the overall vulnerability index.

3.6 Model Validation

To evaluate the success of the DRASTIC vulnerability assessment for evaluating vulnerability to nitrate pollution in the Salinas Valley Groundwater Basin, model results were compared with measured nitrate levels in the Basin. Nitrate data was obtained from CA Geotracker, CA GAMA, and USGS NWIS. For consistency purposes, nitrate data was converted into Nitrate as Nitrate and units of mg/L. The maximum nitrate level measured over the 10-year period from 2007 through 2016 was selected for each well. Wells were then mapped in ArcGIS and overlain by a 2-mile by 2-mile grid. The maximum nitrate measurement per grid was selected and mapped as a point at the centroid of the grid. The measured nitrate levels were then correlated to the DVI value at each point.

4. RESULTS

4.1. Parameters

4.1.1. Depth to Water

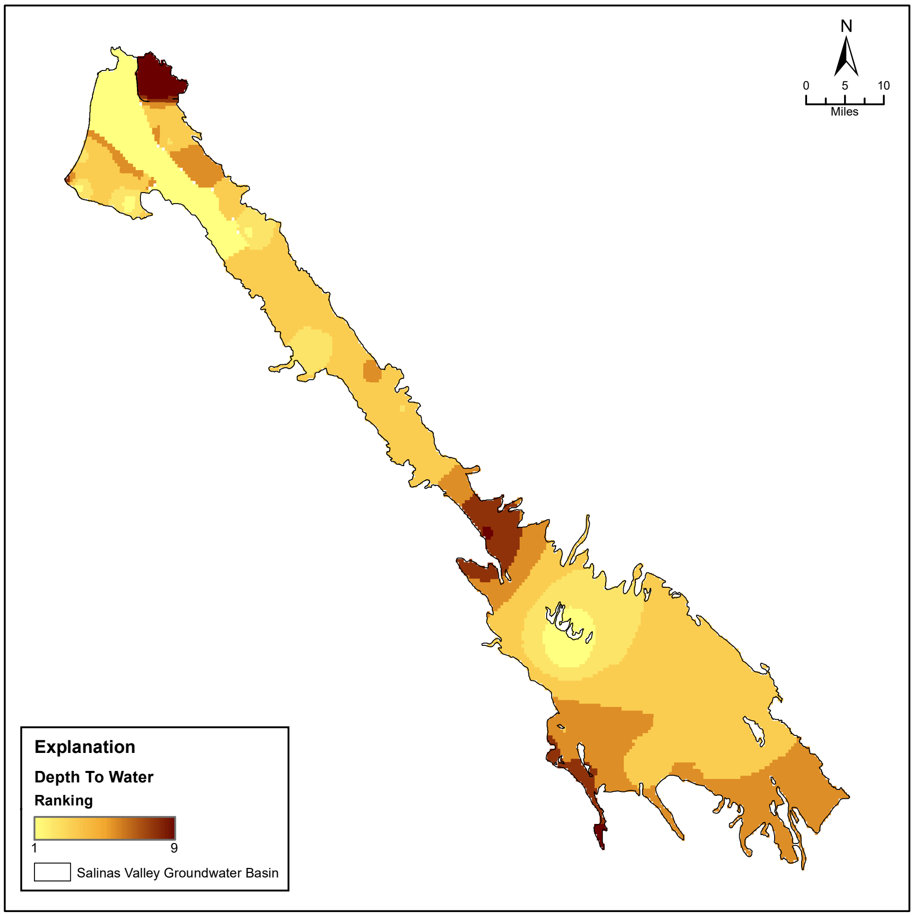

Figure 4-1. Vulnerability of the Depth to Water parameter.

Results of the Depth to Water evaluation are shown in **Figure 4-1**. Depth to water in the Salinas Valley Groundwater Basin ranged from 2.6 feet bgs to 128 feet bgs, resulting in rankings from 1 (low) to 9 (high). The 180/400 Foot Aquifer subbasin in the north of the basin is classified with low depth to water vulnerability, as is expected because of confining conditions. Localized zones of deeper groundwater, and therefore lower vulnerability, are present across the northern portion of the Basin and in the central part of the southern portion of the Basin. The highest depth to water vulnerability occurs in the Langley Area subbasin, the southern portion of the Upper Valley Aquifer subbasin, and the southern tip of the Atascadero Area subbasin, due to shallow groundwater levels.

4.1.2. Net Recharge

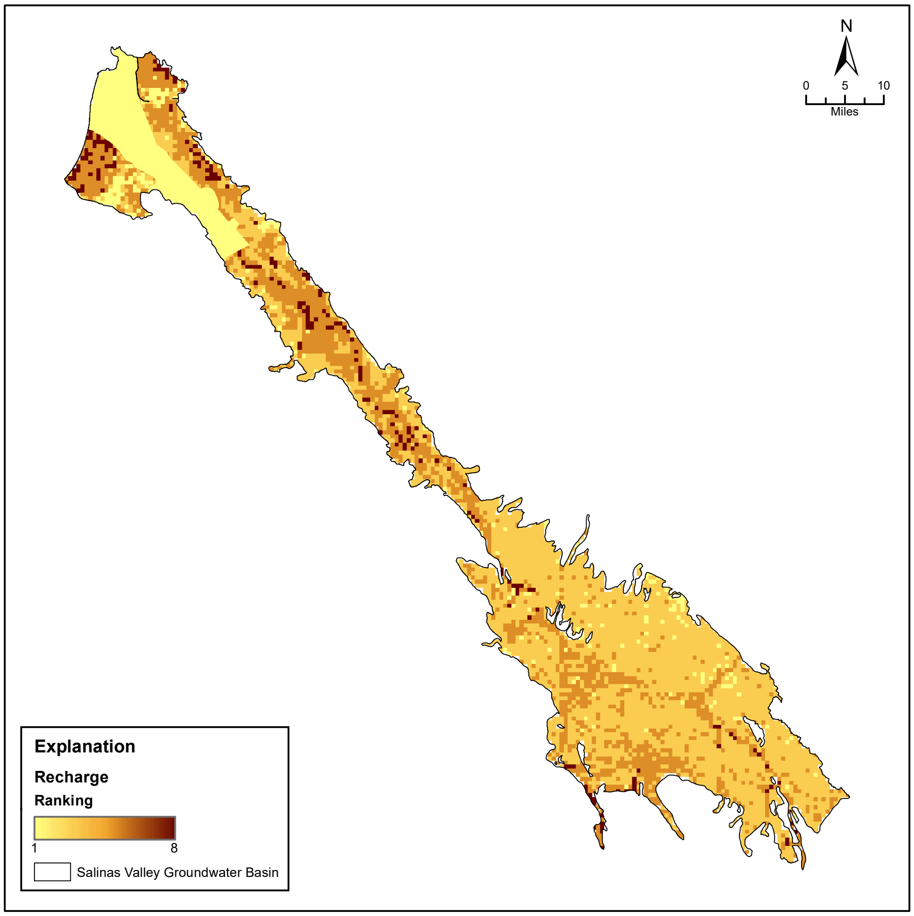

Figure 4-2. Vulnerability of the Net Recharge parameter.

Results of the Net Recharge evaluation are shown in **Figure 4-2**. Net recharge rankings in the Basin range from 1 (low) to 8 (high). The lowest vulnerability is observed in the 180/400 Foot Aquifer subbasin, as to be expected because there is little to no surface recharge due to the confining layer above the aquifer. The majority of the Basin is classified with moderate recharge vulnerability. In general, the northern portion of the Basin has higher vulnerability than the southern portion. The highest vulnerability occurs in the flat valley areas of the Basin, while the foothill and mountainous areas have lower vulnerability. This is due to runoff potential: steeper slopes are more likely to experience runoff, while gentle slopes or flat ground will experience recharge. High vulnerability is also observed along the Salinas River, as is to be expected as it is one of the primary sources of recharge in the Basin.

4.1.3. Aquifer Media

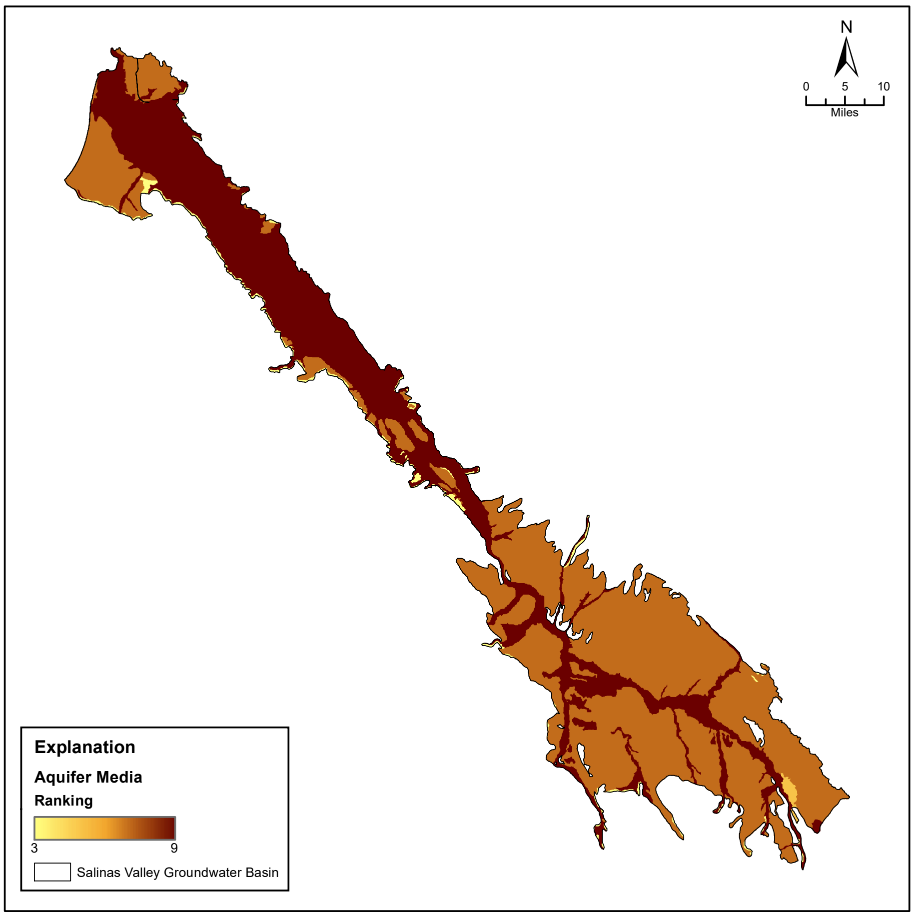

Figure 4-3. Vulnerability of the Aquifer Media parameter.

Results of the Aquifer Media evaluation are shown in **Figure 4-3**. Aquifer media rankings in the Basin range from 3 (low) to 9 (high). The highest vulnerability zones are sands and gravels, comprised of Plio-Pleistocene to recent deposits, located throughout the Basin along the flat valleys. The foothills and mountainous areas, composed primarily of Oligocene to

Pliocene sandstones and shales, have moderate to high vulnerability. Lastly, the lowest vulnerability zones are localized areas of Pre-Cretaceous and Mesozoic bedrock along the mountainous areas at the edges of the Basin.

4.1.4. Soil Media

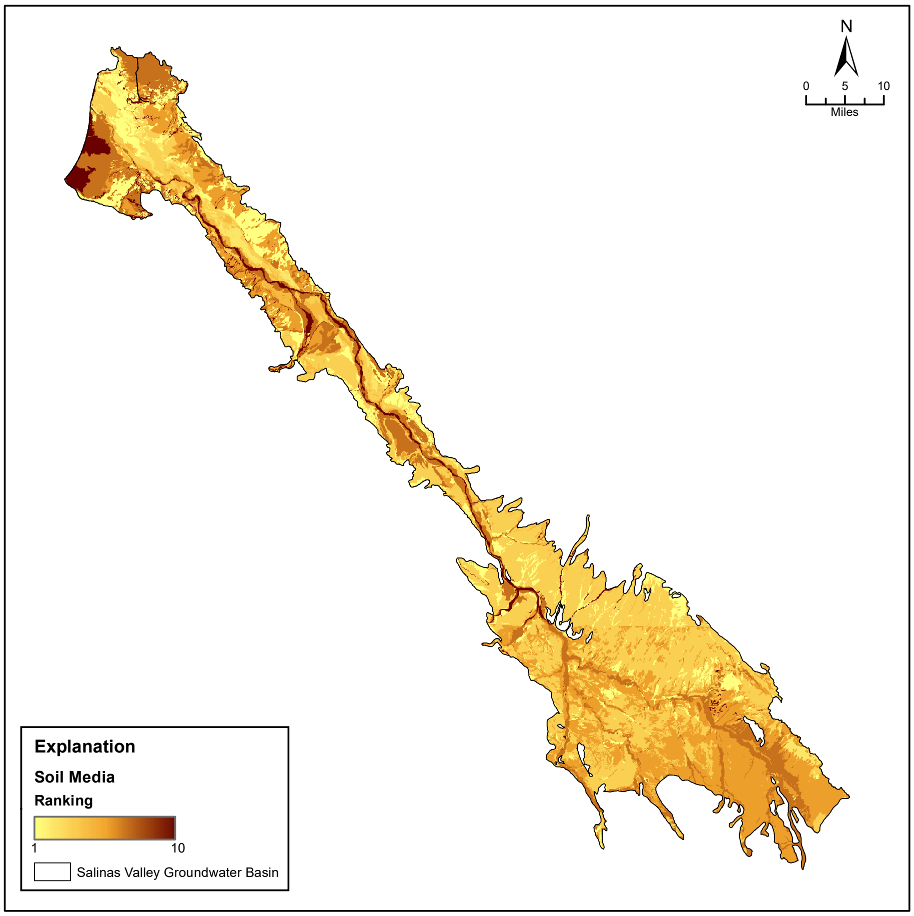

Figure 4-4. Vulnerability of the Soil Media parameter.

Results of the Soil Media evaluation are shown in **Figure 4-4**. Soil media rankings in the Basin range from 1 (low) to 10 (high). Vulnerability due to soil media is highly variable locally. In general, high vulnerability is observed along the Salinas River, as well as along the northern extent of the Basin.

4.1.5. Topography (slope)

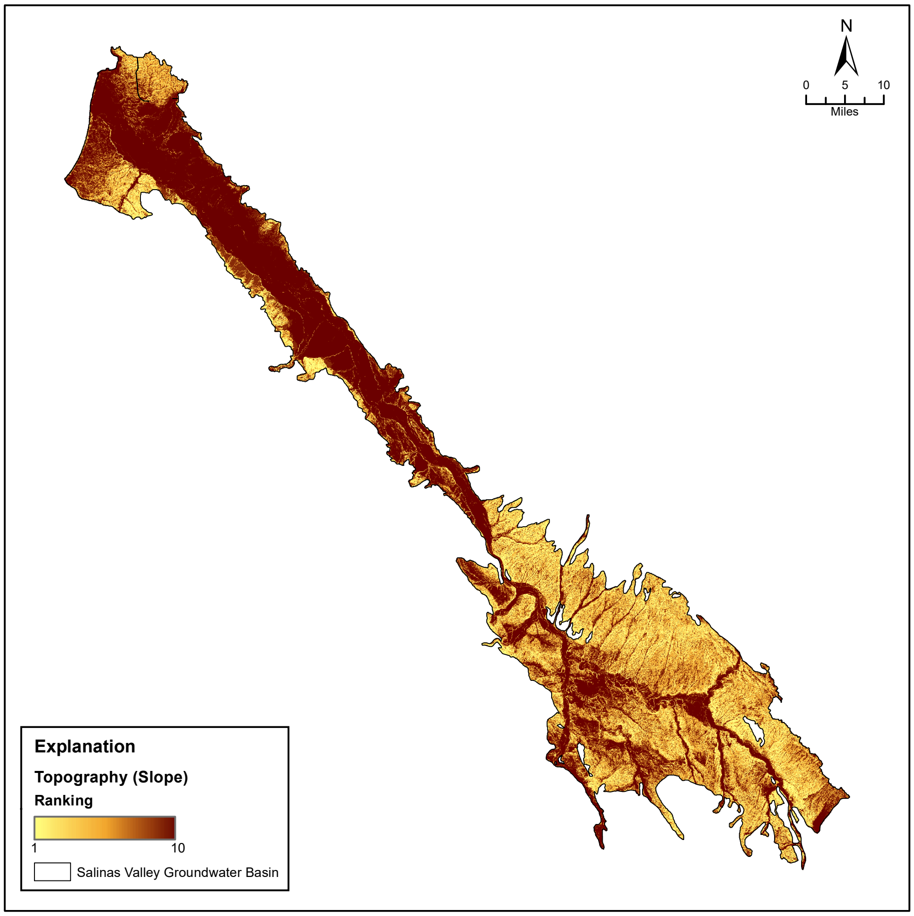

Figure 4-5. Vulnerability of the Topography (slope) parameter.

Results of the Topography evaluation are shown in **Figure 4-5**. Topography rankings in the Basin range from 1 (low) to 10 (high). The highest topography vulnerability is in the flat valley areas, while the foothill and mountainous areas have lower vulnerability. This is again due to runoff potential: steeper slopes are more likely to experience runoff and contaminants are less likely to infiltrate, while gentle slopes or flat ground will experience recharge and contaminants are more likely to enter the subsurface.

4.1.6. Impact of the Vadose Zone

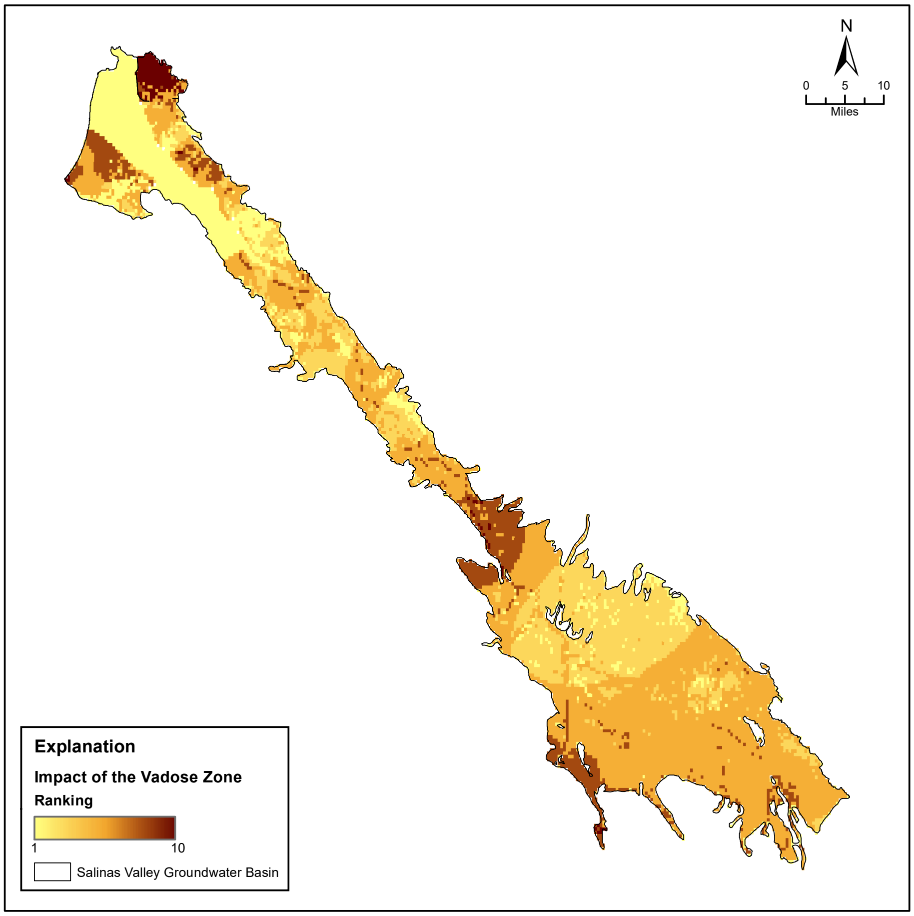

Figure 4-6. Vulnerability of the Impact of the Vadose Zone parameter.

Results of the Impact of the Vadose Zone evaluation are shown in **Figure 4-6**. Impact of the vadose zone rankings in the Basin range from 1 (low) to 10 (high). The 180/400 Foot Aquifer subbasin has low vadose zone vulnerability, as to be expected due to confining conditions. Localized zones of low and high vulnerability are observed, while the majority of the Basin has moderate vadose zone vulnerability. The highest vulnerability is observed along the Salinas River, in the Langley Area subbasin, Atascadero Area subbasin, and in the southern Upper Valley Aquifer subbasin.

4.1.7. Hydraulic Conductivity

Results of the Hydraulic Conductivity evaluation are shown in **Figure 4-7**. Hydraulic conductivity rankings in the Basin range from 1 (low) to 10 (high). The majority of the Basin has moderate to high hydraulic conductivity vulnerability, while zones of low vulnerability are observed in the Seaside, Monterey, southern Upper Valley Aquifer, and southern Paso Robles Area subbasins.

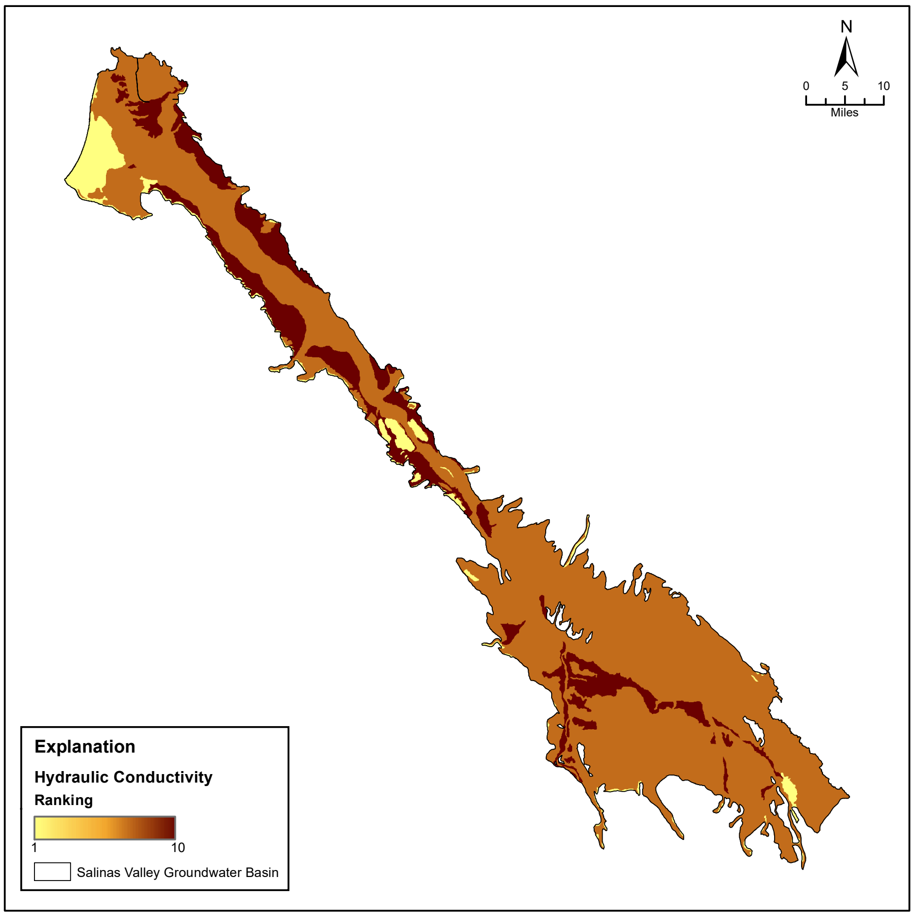

Figure 4-7. Vulnerability of the Hydraulic Conductivity parameter.

4.1.8. Land Use

Results of the Land Use evaluation are shown in **Figure 4-8**. Land use rankings range from 1 (low) to 10 (high). Cotton is ranked highest, followed by irrigated field crops and built up areas. Citrus orchards and orchards of other fruits, vineyards, olives, pasture lands, and temporarily uncultivated land are given a moderate vulnerability rankings. Lastly, natural areas and forests are given a low vulnerability ranking. The majority of the basin is classified with moderate to high vulnerability. The highest vulnerability is observed in the northern half of the Basin, particularly on the east side of the Basin. Localized areas of low vulnerability are observed on the northwest edge of the basin, along the Salinas River, and along the foothills and mountainous areas in the southern portion of the basin.

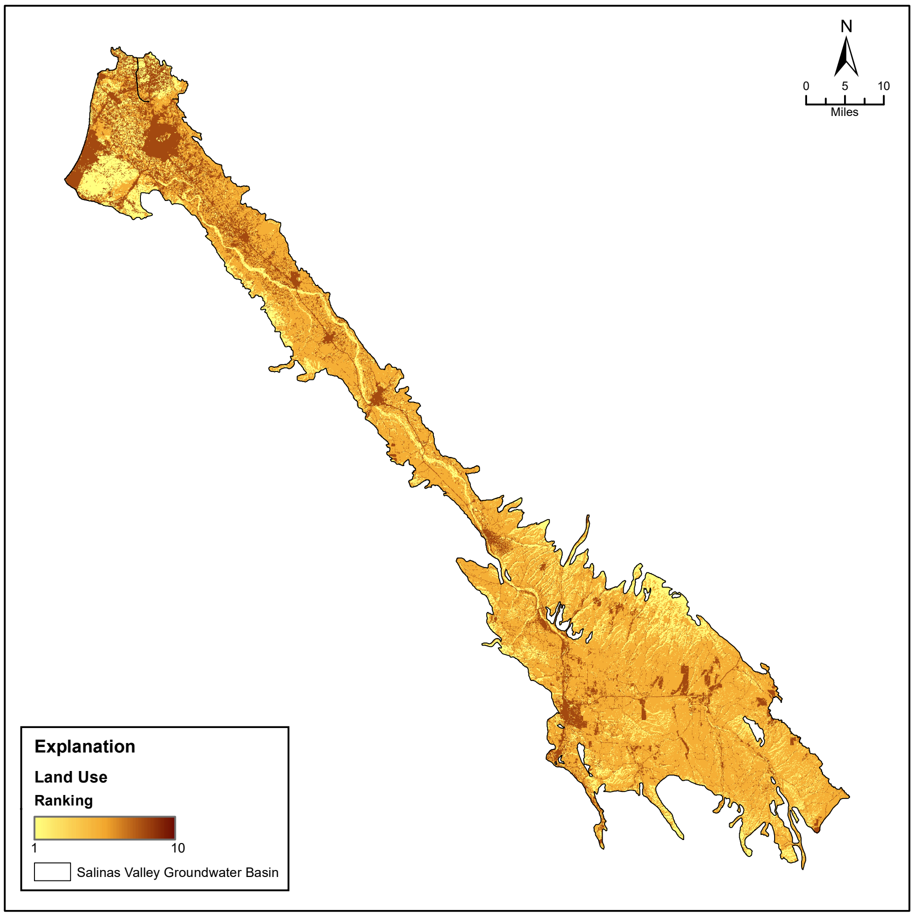

Figure 4-8. Vulnerability of the Land Use parameter.

4.2. DRASTIC Vulnerability Index

The results of the DRASTIC vulnerability assessment are shown in **Figure 4-9**. The majority of the basin is classified with low to moderate vulnerability, with localized zones of very low and high vulnerability. Classifications were assigned to the DVI results as follows: Very Low (43-85.5), Low (85.5-128), Moderate (128-170.5), and High (170.5-213) vulnerability. The distribution of DRASTIC vulnerability classifications is shown in **Figure 4-10**. The Salinas Valley Groundwater Basin was found to have very low vulnerability in 2.9%, low vulnerability in 50.6%, moderate vulnerability in 42.9%, and high vulnerability in 3.6% of the Basin.

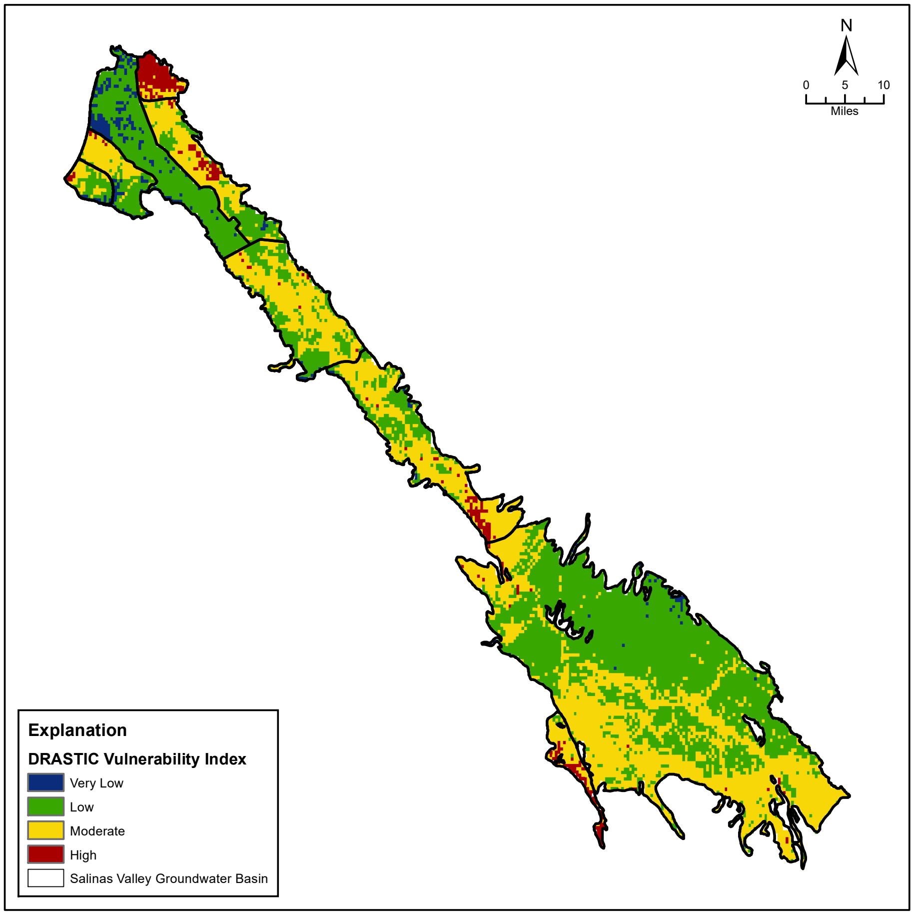

Figure 4-9. DRASTIC Vulnerability Map.

The Langley Area subbasin is the most at risk subbasin to nitrate contamination, with nearly the entire subbasin being classified with high vulnerability. The Atascadero Area subbasin is also at high risk of nitrate contamination, as the entire subbasin is classified with moderate to high vulnerability. Patches of high vulnerability are also observed in the Eastside Aquifer and Upper Valley Aquifer subbasins. Scattered points of high vulnerability are present in localized locations within the Seaside, Monterey, and Forebay Aquifer subbasins. The 180/400 Foot Aquifer subbasin is classified with very low to low vulnerability, as to be expected due to confining conditions. The Paso Robles Area subbasin also has large areas of low vulnerability, likely due to low vulnerability in the depth to water, soil media, topography, impact of the vadose zone, and land use parameters.

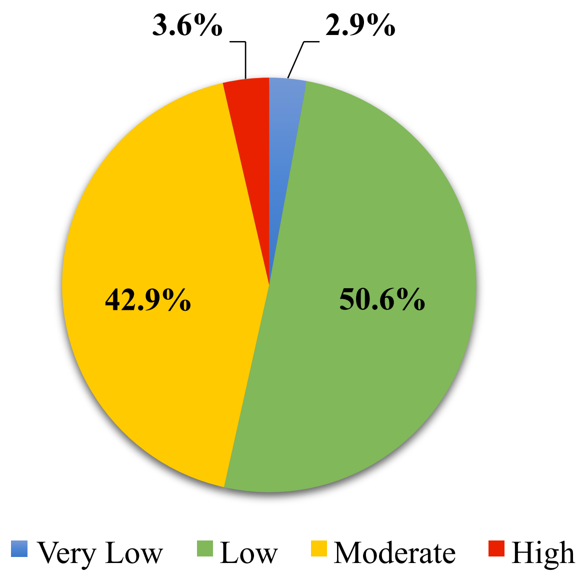

Figure 4-10. Distribution of DRASTIC vulnerability classifications.

4.3. Sensitivity Analysis

A statistical summary of the DRASTIC parameter maps used to determine the DVI is shown in **Table 4-1**. The highest vulnerability to groundwater contamination is from the aquifer media parameter (mean value of 8.35), followed by the hydraulic conductivity parameter (8.05). The topography, land use, impact of the vadose zone, and soil media parameters constitute moderate vulnerability (6.85, 4.78, 4.23, and 4.04, respectively). The lowest vulnerability comes from the net recharge and depth to water parameters (3.47 and 3.36, respectively). The depth to water, impact of the vadose zone, topography, soil media, land use, and net recharge parameters are moderately variable (CV% of 48.83, 48.72, 47.97, 45.62, 44.49, and 43.85, respectively). Meanwhile, the hydraulic conductivity (CV% = 17.92) and aquifer media (CV% = 7.78) parameters have the least variability.

Table 4-1. Statistical summary of the DRASTIC parameter maps.

	D	*R*	*A*	*S*	*T*	*I*	*C*	*LU*
Minimum	1	1	3	1	1	1	1	1
Maximum	9	8	9	10	10	10	10	10
Mean	3.36	3.47	8.35	4.04	6.85	4.23	8.05	4.78
SD	1.64	1.52	0.65	1.84	3.28	2.06	1.44	2.13
CV (%)	48.83	43.85	7.78	45.62	47.97	48.72	17.92	44.49

SD: standard deviation; CV: coefficient of variation

4.3.1 Map Removal Sensitivity Analysis

The results of the map removal sensitivity analysis computed by removing one parameter map at a time are presented in **Table 4-2**. The removal of the topography parameter resulted in the highest variation of the DVI (mean variation index = 2.62%). The removal of the soil media parameter and depth to water parameter also resulted in relatively high variation of the DVI (2.51% and 2.07%, respectively). While these parameters have low weights assigned by DRASTIC (1 and 2, respectively), this variation is likely due to the combination of moderate to high mean vulnerability and high variability.

Table 4-2. Statistics of the map removal sensitivity analysis computed by removing one parameter map at a time.

Parameter Removed	Variation Index (%)			
	Mean	Minimum	Maximum	SD
D	2.07	0.00	20.93	1.99
R	1.93	0.00	8.36	1.16
A	1.01	0.00	6.93	0.64
S	2.51	0.00	8.93	1.14
T	2.62	0.02	7.70	1.03
I	1.51	0.00	8.07	1.19
C	1.08	0.00	8.64	0.77
LU	0.66	0.00	1.93	0.28

SD: standard deviation

The results of the map removal sensitivity analysis computed by cumulatively removing a single parameter map each time are presented in **Table 4-3**. The removal of parameter maps was based on the previous single parameter map removal sensitivity test. Parameter maps contributing the least variation to the DVI, or the parameter with the lowest mean variation index, were preferentially removed. The lowest mean variation resulted from the removal of the land use parameter (0.66%). As more parameters are removed from the DVI equation, the mean variation index increases, as is to be expected. No clear trend in the mean variation index was observed as parameters were removed from the DVI calculation, suggesting that all eight parameters used are necessary for the DVI calculation.

Table 4-3. Statistics of the map removal sensitivity analysis computed by cumulatively removing a parameter map each time.

Parameters used	Variation index (%)			
	Mean	Minimum	Maximum	SD
D,R,A,S,T,I,C	0.66	0.00	1.93	0.28
D,R,S,T,I,C	0.78	0.00	4.74	0.75
D,R,S,T,I	2.31	0.00	8.25	1.64
D,R,S,T	3.58	0.00	8.75	1.35
D,S,T	4.21	0.00	9.17	1.43
S,T	6.52	0.00	12.50	2.00
T	6.93	0.00	12.50	2.90

SD: standard deviation

4.3.2. Single Parameter Sensitivity Analysis

The results of the single parameter sensitivity analysis are presented in **Table 4-4**. All eight parameters showed some deviation from their “theoretical” weight. The aquifer media and hydraulic conductivity parameters are the most effective parameters in the DVI calculation (mean effective weight % of 29.12 and 28.07, respectively). The difference between the “theoretical” weight percentage and “effective” weight percentage for these parameters also varies by the greatest margin, compared to the other parameters. This is likely due to the high vulnerability of these parameters and low variability, as shown in **Table 4-1**. The land use parameter is also observed to have a high “effective” weight (27.79) and exceeds the “theoretical” weight assigned by a wide margin. The other parameters all have an “effective” weight exceeding that of their “theoretical” weight. However, the margin by which they vary is much smaller in comparison to the aquifer media, hydraulic conductivity, and land use parameters.

Table 4-4. Statistics of the single parameter sensitivity analysis.

Parameter	"Theoretical" weight	"Theoretical" weight (%)	"Effective" weight (%)			
			Mean	Minimum	Maximum	SD
D	5	17.86	19.56	5.81	52.33	9.55
R	4	14.29	15.87	0.00	37.21	7.34
A	3	10.71	29.12	0.00	31.40	2.32
S	2	7.14	9.40	0.00	23.26	4.29
T	1	3.57	7.96	0.00	11.63	3.82
I	5	17.86	24.61	5.81	58.14	11.99
C	3	10.71	28.07	0.00	34.88	5.05
LU	5	17.86	27.79	0.00	58.14	12.38

4.4. Model Validation

Measured nitrate values within the Salinas Valley Groundwater Basin are mapped in **Figure 4-11**. In general, a greater number of measurements above the MCL are observed in the northern half of the Basin. By visual comparison, measured nitrate values in the central and southern portions of the Basin appear to match up somewhat well with the DVI. However, measured nitrate values in the northern portion of the Basin do not appear to match up with the DVI. A correlation analysis was performed to evaluate the fit of the DRASTIC vulnerability assessment with measured nitrate values.

Results of the correlation analysis are shown in **Table 4-5**. Nitrate measurements and the DVI show very little correlation (r-value of 0.20, $p \leq 0.05$). Nitrate measurements also show very little correlation with the depth to water parameter (0.24, $p \leq 0.05$). No correlation is shown between nitrate measurements and the other parameters. The non-existent relationship between measured nitrate levels and the land use parameter was a particularly unexpected result of the correlation analysis.

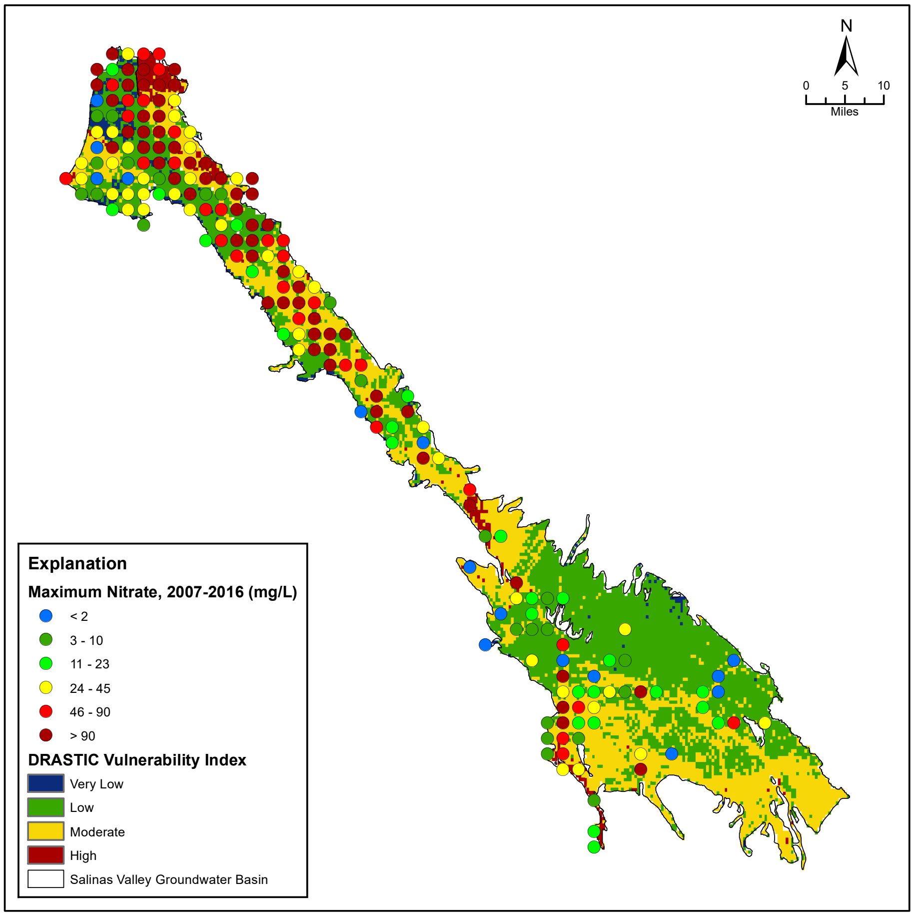

Figure 4-11. DRASTIC vulnerability map and maximum measured nitrate values by 2-mile grid in the Salinas Valley Groundwater Basin.

The correlation of the DVI and DRASTIC parameters is also shown in **Table 4-5**. The DVI shows a strong correlation to impact of the vadose zone (0.89, $p \leq 0.05$) and a weak correlation to depth to water (0.80, $p \leq 0.05$) and net recharge (0.76, $p \leq 0.05$). This is likely due to the high weights assigned to these parameters by DRASTIC. Impact of the vadose zone shows a weak correlation to depth to water (0.77, $p \leq 0.05$) and net recharge (0.67, $p \leq 0.05$). This is likely due to the interaction of these parameters. The impact of the vadose zone relies on both depth to water and soil permeability (a factor in the determination of net recharge). Aquifer media shows a weak correlation to hydraulic conductivity (0.71, $p \leq 0.05$). This is likely due to the similar nature of the parameters. Aquifer media will determine the hydraulic conductivity in an area.

Table 4-5. Correlation coefficients for measured nitrate levels and DRASTIC vulnerability index and parameters.

	NO3	*DVI*	*D*	*R*	*A*	*S*	*T*	*I*	*C*	*LU*
NO3	1.00									
DVI	0.20	1.00								
D	0.24	0.80	1.00							
R	-0.01	0.76	0.47	1.00						
A	0.05	0.02	-0.20	0.01	1.00					
S	-0.05	0.32	0.19	0.37	-0.16	1.00				
T	0.03	0.07	-0.15	0.01	0.57	-0.12	1.00			
I	0.15	0.89	0.77	0.67	-0.22	0.32	-0.09	1.00		
C	0.06	0.10	-0.01	0.02	0.71	-0.20	0.15	-0.12	1.00	
LU	0.09	0.09	0.08	0.01	0.09	-0.11	0.18	0.02	-0.01	1.00

The groundwater vulnerability map produced in this application of DRASTIC could not be validated using measured nitrate concentrations. A great fit is not to be expected using the DRASTIC method. DRASTIC is a linear model that is too simplistic to capture the highly nonlinear behavior of groundwater flow and transport processes. However, the results of this assessment were unexpected, particularly the nonexistent relationship between land use and nitrate. Potential reasons for the poor fit of the DRASTIC vulnerability map in this assessment include: (1) the temporal variability of select DRASTIC parameters, (2) the inability of the land use parameter to accurately represent nitrate vulnerability, (3) the high spatial variability of nitrate contamination in the Salinas Valley Groundwater Basin, and (4) the static weights assigned to parameters by the DRASTIC model.

Changing aquifer characteristics through time will result in different vulnerability patterns through time. It is possible that the data used in this assessment may not be representative of the conditions that existed when current nitrate contamination was introduced at the surface. In particular, depth to water, net recharge, and impact of the vadose zone are variable through time. Land use may also be variable through time. These parameters are the highest weighted in the DVI calculations. Therefore, changes in these parameters will result in changes in the results of the DRASTIC vulnerability assessment. Because nitrate is a persistent contaminant, once it has entered into groundwater, contamination will remain for long periods of time. As a result, the presence and distribution of nitrate in groundwater may not be reflective of the current nitrate sources on the surface.

The land use parameter may have also inaccurately represented nitrate vulnerability. The land use parameter used in this study was adapted from a previous study that originally developed the parameter to represent the risk of contamination to groundwater from extensive agricultural land use. It was not developed specifically for the representation of nitrate contamination. This method was used in this assessment because agricultural land use activities have been shown to be the primary source of nitrate to groundwater within the Salinas Valley Groundwater Basin. However, it is possible that this method to develop a land use parameter was not able to accurately represent groundwater vulnerability to nitrate pollution from agricultural activities within the Basin. The generalized groupings of land use types may not reflect the specific risk of nitrate contamination from each land use type. Therefore, underestimations and overestimations of the risk of nitrate contamination are likely, resulting in inaccurate DVI results.

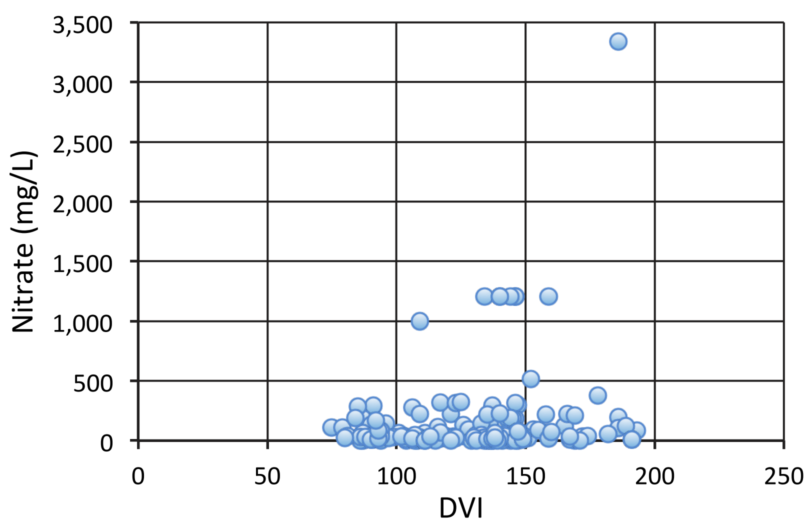

Figure 4-12. Correlation graph of measured nitrate values and DVI.

Additionally, the high spatial variability of nitrate contamination in the Salinas Valley Groundwater Basin could contribute to the inability to fit the model to measured nitrate levels. The relationship between measured nitrate concentrations and the DVI is shown in **Figure 4-12**.

It is clearly apparent that nitrate occurs at various concentrations across all levels of DRASTIC vulnerability. Therefore, high nitrate concentrations can occur in high vulnerability areas as well as in low vulnerability areas, just as low concentrations can also occur in both areas. The simplistic nature of the DRASTIC model is not capable of handling the complex nature of the high spatial variability of nitrate contamination in the Salinas Valley.

Finally, the static weights assigned by DRASTIC to parameters could result in an inaccurate vulnerability assessment. By design, the weights assigned by DRASTIC to each parameter are static values that have been determined based on the relative importance of each parameter with respect to the other parameters. Because the DRASTIC model was designed for a generic situation, the relative importance of each parameter is generic. However, the actual importance of each parameter is likely to change in different groundwater basins with different aquifer characteristics. Because the weights are assigned generically and not based on the data, the weights may not accurately represent the importance of each parameter to the specific basin being evaluated. Thus, the emphasis of each parameter to the overall DVI may be inaccurate, resulting in an inaccurate vulnerability assessment.

4.5 Errors and Uncertainty

Throughout this assessment, there are potential sources of error and uncertainty that could have affected the results of the assessment.

Data for this assessment was collected from publically available sources only. It is acknowledged that various private sources, as have been used in previous studies, were not incorporated in this analysis. As a result, the data is not as complete as possible. Furthermore, the presence of outliers in the datasets is possible, particularly in the groundwater level and nitrate level data. Outliers could produce skewed results, as they are not representative of regional conditions within the Basin.

Interpretations of the data were also necessary in some cases, particularly within the geology and soil datasets. Additionally, hydraulic conductivity values were estimated based on the geology data. Decisions were made to group the various geologic units and soil units under the correct DRASTIC categories based on literature reviews. However, it is possible that the characteristics of these units vary spatially, and do not have the same vulnerability in all occurrences. This variability may not have been accurately captured in this assessment.

Additionally, the time period of data used also contributes to uncertainty. Groundwater level data was taken from the 2016 water year. 2016 marked the fifth year of drought in California, with the Salinas Valley experiencing extreme to exceptional drought conditions. During times of drought, groundwater levels will be depleted. Because groundwater levels influence the depth to water and impact of the vadose zone parameters, the two highest weighted parameters by DRASTIC, the results of the vulnerability assessment are skewed toward lower vulnerability.

5. CONCLUSIONS & RECOMMENDATIONS

In this application of DRASTIC, the vulnerability assessment was not able to be validated using measured nitrate levels. As DRASTIC is a vulnerability assessment model, it is not intended to map current contamination. However, the results of this assessment are unexpected. The DVI has very low correlation with measured nitrate levels, while the land use parameter has no correlation with nitrate. Four possible reasons for the poor fit of this assessment have been identified: (1) the temporal variability of select DRASTIC parameters, (2) the inability of the land use parameter to accurately represent nitrate vulnerability, (3) the high spatial variable of nitrate contamination in the Salinas Valley Groundwater Basin, and (4) the static weights assigned to parameters by the DRASTIC model.

While the addition of a land use parameter was intended to model nitrate vulnerability, it is likely that the method used in this assessment was not adequate in representing the true risk of nitrate contamination within the Salinas Valley. Improvements could be made to the land use parameter by adding a nitrate-loading component. Average nitrate loading for each land use type could be determined and rankings could be assigned based on the amount of nitrate being applied at the surface. Additionally, irrigation could also be considered in an attempt to model the potential for nitrate leaching. Such a nitrate leaching parameter could be further improved by using values specific to the basin being evaluated, rather than generic values for a given crop type.

The data used to create the parameter layers used in production of the DRASTIC vulnerability map may not be representative of the conditions that existed when nitrate concentrations currently in groundwater were introduced at the surface. Nitrate is a persistent contaminant, and contamination issues can persist in groundwater for years to decades after the initial introduction of the contaminant. While parameters such as aquifer media, soil media, topography, and hydraulic conductivity are unlikely to change over time, parameters such as depth to water, net recharge, the impact of the vadose zone, and land use are variable through time. Because the depth to water, net recharge, impact of the vadose zone, and land use parameters are the highest weighted DRASTIC parameters, changes in these parameters will change the results of the DRASTIC assessment through time.

Furthermore, while the addition of a land use parameter was intended to model nitrate vulnerability, it is likely that the method used in this assessment was not adequate in representing the true risk of nitrate contamination within the Salinas Valley. Improvements could be made to the land use parameter by adding a nitrate-loading component. Average nitrate loading for each land use type could be determined and rankings could be assigned based on the amount of nitrate being applied at the surface. Additionally, irrigation could also be considered in an attempt to model the potential for nitrate leaching. Such a nitrate leaching parameter could be further improved by using values specific to the basin being evaluated, rather than generic values for a given crop type.

Finally, the simplicity of the DRASTIC model proved incapable of handling the complexities associated with nitrate distribution in the Salinas Valley. The high spatial variability of nitrate contamination in the Basin is not accounted for in this vulnerability assessment. While a more complex model would better represent this variability, improvements to the weights assigned to the DRASTIC parameters could also produce a better fit. The weights assigned to each parameter are not based on the data, but rather are static values representing generic situations. To derive weights based on the data, a multiple linear regression could be performed to determine the true impact of each parameter with respect to nitrate contamination in the Basin. By calibrating the weights using measured nitrate levels in the Basin, the new weights will better represent the true impact of each parameter relative to the others in the overall vulnerability calculation and will result in a more accurate vulnerability assessment.

Although the DRASTIC vulnerability assessment was not successful in representing nitrate vulnerability, nitrate management strategies should be employed in agricultural areas of the Salinas Valley Groundwater Basin. Previous studies have demonstrated that agricultural activities are the primary source of nitrate to groundwater within the Basin. Therefore, management strategies for the prevention and reduction of nitrate should be targeted in agricultural areas.

The most commonly recommended strategy for both the prevention and reduction of nitrate contamination are land use changes. As is the case in the Salinas Valley, agriculture is often a primary source of nitrate to groundwater. Therefore, a reduction or removal of the source, in this case agricultural activities, would help to prevent and lessen the continued effects of nitrate contamination. However, as agriculture is a multi-billion dollar industry in, and the economic backbone of, the Salinas Valley, land use changes are not likely to be feasible options for the management and prevention of nitrate contamination. It is therefore recommended that nitrate management strategies be adopted into the current land use strategies employed within the Basin.

A nitrate management strategy that could be particularly beneficial in the Salinas Valley is the pump-and-fertilize method. The pump-and-fertilize method is a groundwater remediation strategy that aims to not only remediate contaminated groundwater, but works to reduce the introduction of nitrate at the surface. This method works by employing existing nitrate best management practices to maximize nitrogen use efficiency, while also accounting for the nitrate already present in irrigation water when calculating fertilizer needs (King et al., 2012). The intention is to utilize the nitrate already present in irrigation waters in order to reduce applied nitrogen fertilizers. As a result of this practice, excess nitrate for leaching is reduced and contaminant inputs are reduced. Additionally, crops can utilize the nitrate present in irrigation water and nitrate is removed from the system, thus lowering the concentrations of nitrate in groundwater.

Drawbacks of the pump-and-fertilize method include the extensive monitoring of irrigation waters in order to properly account for this nitrate source, as well as the technical expertise required for the calculation of fertilizer needs. Educational and financial support is necessary in order to implement the widespread use of this method. Training is necessary to ensure that farmers are equipped to calculate the contribution of nitrate from irrigation water and the resultant fertilizer needs. Additionally, it will be a challenge to ensure that farmers have the equipment necessary for the monitoring of nitrate in irrigation waters. While the widespread implementation of the pump-and-fertilize method will be a difficult process, it is the best method to not only remediate nitrate contamination and sources, but to ensure that agriculture may continue in the Salinas Valley in a sustainable manner.

6. SOURCES

Akhavan, Samira, Sayed Farhad Mousavi, Jahangir Abedi-Koupai, and Karim C. Abbaspour. 2011. “Conditioning DRASTIC Model to Simulate Nitrate Pollution Case Study: Hamadan-Bahar Plain.” *Environmental Earth Sciences* 63 (6): 1155–67. doi:10.1007/s12665-010-0790-1.

Aller, Linda, Truman Bennett, Jay H. Lehr, Rebecca J. Petty, and Glen Hackett. 1987. “DRASTIC : A Standardized Method for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings.” *NWWA/Epa-600/2-87-035*, 455.

Almasri, Mohammad N., and Jagath J. Kaluarachchi. 2004. “Assessment and Management of Long-Term Nitrate Pollution of Ground Water in Agriculture-Dominated Watersheds.” *Journal of Hydrology* 295 (1–4): 225–45. doi:10.1016/j.jhydrol.2004.03.013.

Almasri, Mohammad N., and Jagath J. Kaluarachchi. 2007. “Modeling Nitrate Contamination of Groundwater in Agricultural Watersheds.” *Journal of Hydrology* 343 (3–4): 211–29. doi:10.1016/j.jhydrol.2007.06.016.

Appelo, C. Anthony J., and Dieke Postma. 2004. “Geochemistry, groundwater and pollution”. Second edition. CRC press.

Babiker, Insaf S., Mohamed A A Mohamed, Tetsuya Hiyama, and Kikuo Kato. 2005. “A GIS-Based DRASTIC Model for Assessing Aquifer Vulnerability in Kakamigahara Heights, Gifu Prefecture, Central Japan.” *Science of the Total Environment* 345 (1–3): 127–40. doi:10.1016/j.scitotenv.2004.11.005.

Böhlke, John Karl. 2002. “Groundwater Recharge and Agricultural Contamination.” *Hydrogeology Journal* 10 (1): 153–79. doi:10.1007/s10040-001-0183-3.

Boyle, D., King, A., Kourakos, G., Lockhart, K., Mayzelle, M., Fogg, G.E. & Harter, T. (2012) Groundwater Nitrate Occurrence. Technical Report 4 in: Addressing Nitrate in California’s Drinking Water with a Focus on Tulare Lake Basin and Salinas Valley Groundwater. Report for the State Water Resources Control Board Report to the Legislature. Center for Watershed Sciences, University of California, Davis.

Brown and Caldwell. 2015. “State of the Salinas River Groundwater Basin.” Salinas, Ca.

CA Department of Water Resources (CA DWR)-A. 2004. “Salinas Valley Groundwater Basin, Corral de Tierra Area Subbasin.” *California’s Groundwater Bulletin 118*.

CA DWR-B. 2004. “Salinas Valley Groundwater Basin, Seaside Area Subbasin.” *California’s Groundwater Bulletin 118*.

CA DWR-C. 2004. “Salinas Valley Groundwater Basin, 180/400 Foot Aquifer Subbasin.” *California’s Groundwater Bulletin 118*.

CA DWR-D. 2004. “Salinas Valley Groundwater Basin, Langley Area Subbasin.” *California’s Groundwater Bulletin 118*.

CA DWR-E. 2004. “Salinas Valley Groundwater Basin, Eastside Aquifer Subbasin.” *California’s Groundwater Bulletin 118*.

CA DWR-F. 2004. “Salinas Valley Groundwater Basin, Forebay Aquifer Subbasin.” *California’s Groundwater Bulletin 118*.

CA DWR-G. 2004. “Salinas Valley Groundwater Basin, Upper Valley Aquifer Subbasin.” *California’s Groundwater Bulletin 118*.

CA DWR-H. 2004. “Salinas Valley Groundwater Basin, Paso Robles Area Subbasin.” *California’s Groundwater Bulletin 118*.

CA DWR-A. 2016. “3-004.10 Salinas Valley - Monterey.”

CA DWR-B. 2016. “California’s Groundwater Working Toward Sustainability: Bulletin 118 Interim Update 2016.”

CA DWR. 2016. Water Data Library data available on the World Wide Web. Accessed December 3, 2016 at http://www.water.ca.gov/waterdatalibrary/.

California State Water Resources Control Board (SWRCB). 2016. Geotracker-GAMA Groundwater Information System data available on the World Wide Web. Accessed December 3, 2016 at http://geotracker.waterboards.ca.gov/gama/.

Chen, Shufeng, Wenliang Wu, Kelin Hu, and Wei Li. 2010. “The Effects of Land Use Change and Irrigation Water Resource on Nitrate Contamination in Shallow Groundwater at County Scale.” *Ecological Complexity* 7 (2). Elsevier B.V.: 131–38. doi:10.1016/j.ecocom.2010.03.003.

Colins, Johnny, M C Sashikkumar, P A Anas, and M Kirubakaran. 2016. “GIS-Based Assessment of Aquifer Vulnerability Using DRASTIC Model: A Case Study on Kodaganar Basin.” *Earth Sciences Research Journal* 20 (1): H1–8. http://10.0.60.86/esrj.v20n1.52469%0Ahttp://search.ebscohost.com/login.aspx?direct=true&db=zbh&AN=118322267&site=ehost-live.

Durbin, Timothy J., Glenn W. Kapple, and John R. Freckleton. 1978. “Two-Dimensional and Three-Dimensional Digital Flow Models of the Salinas Valley Ground-Water Basin, California.” *Water Resources Investigations Report 78-113*, 134 p.

Durham, David L. 1974. “Geology of the Southern Salinas Valley Area, California.” *U.S. Geological Survey Professional Paper 819*.

Gardner, Kristin K., and Richard M. Vogel. 2005. "Predicting Ground Water Nitrate Concentration from Land Use." *Ground Water* 43 (3): 343–52. doi:10.1111/j.1745-6584.2005.0031.x.

Goldrath, Dara A., Justin T. Kulongoski, and Tracy A. Davis. 2017. "Groundwater-Quality Data in the Monterey – Salinas Shallow Aquifer Study Unit , 2013 : Results from the California GAMA Program."

Harter, Thomas, Jay R. Lund, Jeannie Darby, Graham E. Fogg, Richard Howitt, Katrina K. Jessoe, G. Stuart Pettygrove, James F. Quinn, and Joshua H. Viers. 2012. "Addressing Nitrate in California's Drinking Water with a Focus on Tulare Lake Basin and Salinas Valley Groundwater." *Report for the State Water Resources Control Board Report to the Legislature*, 1–78. http://groundwaternitrate.ucdavis.edu/files/138956.pdf.

Heath, Ralph C. 1983. "Basic Ground-Water Hydrology." *U.S. Geological Survey Water-Supply Paper 2220*.

HydroFocus, Inc. 2014. "Distribution of Groundwater Nitrate Concentrations Salinas Valley , California." Davis, CA.

Jamrah, Ahmad, Ahmed Al-Futaisi, Natarajan Rajmohan, and Saif Al-Yaroubi. 2008. "Assessment of Groundwater Vulnerability in the Coastal Region of Oman Using DRASTIC Index Method in GIS Environment." *Environmental Monitoring and Assessment* 147 (1–3): 125–38. doi:10.1007/s10661-007-0104-6.

Javadi, Saman, Neda Kavehkar, Kourosh Mohammadi, Ahmad Khodadadi, and Rene Kahawita. 2011. "Calibrating DRASTIC Using Field Measurements, Sensitivity Analysis and Statistical Methods to Assess Groundwater Vulnerability." *Water International* 36 (6): 719–32. doi:10.1080/02508060.2011.610921.

Jennings, C.W., 1958, Geologic map of California - San Luis Obispo Quadrangle, California Division of Mines and Geology, 1:250,000 scale.

Jennings, C.W. and Strand, R.G. , 1958, Geologic Atlas of California - Santa Cruz Quadrangle, California Geological Survey, Geologic Atlas of California Map No. 020, 1:250,000 scale.

Kerna, Ashley, Ruzanna Yolyan, Elizabeth Fadali, George Buddy W Borden, and Thomas R Harris. 2009. "Monterey County, California: Demographic and Economic Description."

King, A., Boyle, D., Jensen, V., Fogg, G. E., & Harter, T. (2012). *Groundwater Remediation and Management for Nitrate*. Technical Report 5 in Addressing Nitrate in: California's Drinking Water with a Focus on Tulare Lake Basin and Salinas Valley Groundwater. Report for the State Water Resources Control Board Report to the Legislature. Center for Watershed Sciences, University of California, Davis.

Kulongoski, Justin T., and Kenneth Belitz. 2011. “Status and Understanding of Groundwater Quality in the Monterey Bay and Salinas Valley Basins, 2005: California GAMA Priority Basin Project.” *Scientific Investigations Report 2011 – 5058*.

Kumar, Prashant, Praveen K. Thakur, Baban K S Bansod, and Sanjit K. Debnath. 2016. “Assessment of the Effectiveness of DRASTIC in Predicting the Vulnerability of Groundwater to Contamination: A Case Study from Fatehgarh Sahib District in Punjab, India.” *Environmental Earth Sciences* 75 (10). Springer Berlin Heidelberg: 1–13. doi:10.1007/s12665-016-5712-4.

Lerner, David N., and Bob Harris. 2009. “The Relationship between Land Use and Groundwater Resources and Quality.” *Land Use Policy* 26 (SUPPL. 1): 265–73. doi:10.1016/j.landusepol.2009.09.005.

Lodwick, W., W. Monson, and L. Svoboda. 1990. “Attribute Error and Sensitivity Analysis of Map Operations in Geographical Information Systems.” *Geographical Information Systems* 4 (4): 413–28. doi:10.1080/02693799008941556.

Luhdorff & Scalmanini Consulting Engineers (LSCE). 2015. “Distribution of Groundwater Nitrate Concentrations, Salinas Valley, California.” Prepared for Central Coast Groundwater Coalition.

Martin, Julie Nico. 2014. “Groundwater Issues Along California’s Central Coast.”

McLay, C. D A, R. Dragten, G. Sparling, and N. Selvarajah. 2001. “Predicting Groundwater Nitrate Concentrations in a Region of Mixed Agricultural Land Use: A Comparison of Three Approaches.” *Environmental Pollution* 115 (2): 191–204. doi:10.1016/S0269-7491(01)00111-7.

Moran, Jean E, Bradley K Esser, Marianne Holtz, K Sarah, Michael J Singleton, and Ate Visser. 2011. “California GAMA Special Study : Nitrate Fate and Transport in the Salinas Valley,” 52.

Napolitano, P, and A G Fabbri. 1996. “Single-Parameter Sensitivity Analysis for Aquifer Vulnerability Assessment Using DRASTIC and SINTACS.” In *HydroGIS 96: Application of Geographic Information Systems in Hydrology and Water Resources Management (Proceedings of the Vienna Conference, April 1996)*. IAHS Publ. no. 235.

Natural Resources Conservation Service (NRCS). 2014. “SSRI – Technical Note Number 26 (3rd Revision). *US Department of Agriculture.*

Natural Resources Conservation Service (NRCS). 2016. Soil Survey Geographic Database (SSURGO) data available on the World Wide Web. Accessed December 3, 2016 at https://www.nrcs.usda.gov/wps/portal/nrcs/surveylist/soils/survey/state/?stateId=CA.

NGWA. 2016. “Groundwater Use in California,” 2 p.

Nolan, Bernard T., Kerie J. Hitt, and Barbara C. Ruddy. 2002. "Probability of Nitrate Contamination of Recently Recharged Groundwaters in the Conterminous United States." *Environmental Science and Technology* 36 (10): 2138–45. doi:10.1021/es0113854.

Panagopoulos, G. P., Anton K. Antonakos, and N. J. Lambrakis. 2006. "Optimization of the DRASTIC Method for Groundwater Vulnerability Assessment via the Use of Simple Statistical Methods and GIS." *Hydrogeology Journal* 14 (6): 894–911. doi:10.1007/s10040-005-0008-x.

Piscopo, Gennaro. 2001. "Groundwater Vulnerability Map Explanatory Notes - Lachlan Catchment." New South Wales, Australia.

Planert, Michael and Williams, John S.. 1995. Groundwater Atlas of the United States: California, Nevada. U.S. Geological Survey. HA 730-B.

PRISM Climate Group. 2016. 30-Year Normal Precipitation data available on the World Wide Web. Accessed December 3, 2016 at http://prism.oregonstate.edu/normals/.

Power, J. F., and J. S. Schepers. 1989. "Nitrate Contamination of Groundwater in North America." *Agriculture, Ecosystems & Environment* 26 (3–4): 165–87. doi:10.1016/0167-8809(89)90012-1.

Remesan, Renji, and R.K. Panda. 2008. "Groundwater Vulnerability Assessment, Risk Mapping, and Nitrate Evaluation in a Small Agricultural Watershed: Using the DRASTIC Model and GIS." *Environmental Quality Management*, 53–75. doi:10.1002/tqem.

RMC. 2006. "Salinas Valley Integrated Regional Water Management Functionally Equivalent Plan Update." http://www.mpwmd.dst.ca.us/mbay_irwm/irwm_library/Salinas_Valley_FEP_May_2006.pdf.

RMC and Luhdorff & Scalmanini Consulting Engineers. 2006. "Monterey County Groundwater Management Plan."

Rupert, Michael G. 2001. "Calibration of the DRASTIC Ground Water Vulnerability Mapping Model." *Ground Water* 39 (4): 625–30.

Sadat-Noori, Mahmood, and Kumars Ebrahimi. 2016. "Groundwater Vulnerability Assessment in Agricultural Areas Using a Modified DRASTIC Model." *Environmental Monitoring and Assessment* 188 (1): 19. doi:10.1007/s10661-015-4915-6.

Salinas Valley Ground Water Basin Hydrology Conference. 1995. "Hydrogeology and Water Supply of Salinas Valley."

Samara, T, and G Yoxas. 2013. "DRASTIC Method to Map Groundwater Vulnerability to Pollution Using Nitrate Measurements in Agricultural Areas." In *Bulletin of the Geological Society of Greece. Proceedings of the 13th International Congress.*, XLVII:981–91.

Secunda, S, M.L Collin, and A.J Melloul. 1998. "Groundwater Vulnerability Assessment Using a Composite Model Combining DRASTIC with Extensive Agricultural Land Use in Israel's Sharon Region." *Journal of Environmental Management* 54 (1): 39–57. doi:10.1006/jema.1998.0221.

Sener, Erhan, Sehnaz Sener, and Aysen Davraz. 2009. "Assessment of Aquifer Vulnerability Based on GIS and DRASTIC Methods: A Case Study of the Senirkent-Uluborlu Basin (Isparta, Turkey)." *Hydrogeology Journal* 17 (8): 2023–35. doi:10.1007/s10040-009-0497-0.

Srinivasamoorthy, K., K. Vijayaraghavan, M. Vasanthavigar, V. S. Sarma, R. Rajivgandhi, S. Chidambaram, P. Anandhan, and R. Manivannan. 2010. "Assessment of Groundwater Vulnerability in Mettur Region, Tamilnadu, India Using Drastic and GIS Techniques." *Arabian Journal of Geosciences* 4 (7–8): 1215–28. doi:10.1007/s12517-010-0138-x.

Tesoriero, Anthony J., and Frank D. Voss. 1997. "Predicting the Probability of Elevated Nitrate Concentrations in the Puget Sound Basin: Implications for Aquifer Susceptibility and Vulnerability." *Groundwater* 35 (6): 1029–39.

U.S. Census Bureau. 2017. "QuickFacts: Monterey County." Accessed March 10, 2017 at https://www.census.gov/quickfacts/table/PST045215/06053.

U.S. Department of Agriculture (USDA). 2012. "2012 Census of Agriculture County Profile: Monterey County, California." National Agricultural Statistics Service.

USDA. 2016. Cropland Data Layer (CDL) data available on the World Wide Web. Accessed December 3, 2016 at https://www.nass.usda.gov/Research_and_Science/Cropland/Release/.

U.S. Environmental Protection Agency (EPA). 2016. *Table of Regulated Drinking Water Contaminants.* <https://www.epa.gov/ground-water-and-drinking-water/table-regulated-drinking-water-contaminants> Accessed 3/3/2017.

U.S. Geological Survey (USGS). 2016. National Elevation Dataset data available on the World Wide Web (The National Map). Accessed December 3, 2016 at https://nationalmap.gov/elevation.html.

U.S. Geological Survey (USGS). 2016. National Water Information System data available on the World Wide Web (USGS Groundwater Data for the Nation). Accessed December 3, 2016 at https://waterdata.usgs.gov/nwis/gw.

Weiner, Eugene R. 2013. *Applications of Environmental Aquatic Chemistry: A Practical Guide*. Third Edit. CRC Press.

Wilmarth, M. Grace. 1931. “Names and Definitions of the Geologic Units of California.” *US Geological Survey Bulletin 826*, 97.

Yin, Lihe, Eryong Zhang, Xiaoyong Wang, Jochen Wenninger, Jiaqiu Dong, Li Guo, and Jinting Huang. 2013. “A GIS-Based DRASTIC Model for Assessing Groundwater Vulnerability in the Ordos Plateau, China.” *Environmental Earth Sciences* 69 (1): 171–85. doi:10.1007/s12665-012-1945-z.